MECHANICAL SYSTEMS READINESS ASSESSMENT

AND PERFORMANCE MONITORING STUDY

FINAL REPORT

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Details of illustrations in
this document may be better
studied on microfiche

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336

ABSTRACT

This document is the final report for the John F. Kennedy Space Center Study, "Mechanical Systems Readiness Assessment and Performance Monitoring". This study dealt with the problem of mechanical devices which lack the real-time readiness assessment and performance monitoring capability required for future space missions. Structure Borne Acoustics is a non-destructive test techniques that shows promise for helping alleviate this problem. This report describes the results of a test program configured to establish the practical feasibility of implementing Structure Borne Acoustics on future space programs.

The test program included the monitoring of operational acoustic signatures of five separate mechanical components, each possessing distinct sound characteristics, e.g., cyclic, transient, and flow noise. Acoustic signatures were established for normal operation of each component. Critical failure modes were then inserted into the test components, and faulted acoustic signatures obtained.

Predominant features of the sound signature were related back to operational events occurring within the components both for normal and failure mode operations. Analysis of these signatures permitted the establishment of parameter limits that can be used to make readiness assessment decisions. All of these steps can be automated. Thus, the Structure Borne Acoustics technique, although having certain limitations, lends itself to reducing checkout time, simplifying maintenance procedures, and reducing manual involvement in the checkout, operation, maintenance, and fault diagnosis of mechanical systems. A discussion of methods and estimated costs for implementing this non-destructive test technique on future space programs is also presented in this report.

FOREWORD

This report summarizes the results of the "Mechanical Systems Readiness Assessment and Performance Monitoring" study conducted under Kennedy Space Center Contract NAS10-7788. The KSC Technical Representative for this study is R. A. Sannicandro, DD-SED-4, telephone—(305) 867-2102. The study was conducted by the following General Electric Company personnel:

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MECHANICAL SYSTEMS READINESS
ASSESSMENT AND PERFORMANCE
MONITORING STUDY

FINAL REPORT

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

SECTION I

INTRODUCTION

1.1 SCOPE

This report presents a summation of study tasks performed by the General Electric Company during the period October 21, 1971 through May 19, 1972 for the John F. Kennedy Space Center Study, "Mechanical Systems Readiness Assessment and Performance Monitoring".

1.2 BACKGROUND INFORMATION

To support future space program plans for real-time status monitoring, fault isolation/prediction, and an automatic checkout capability superior to that employed for previous space programs must be developed and implemented. This capability cannot be achieved unless the system end-item components can communicate their status. Mechanical devices which are essential to both airborne and ground equipment operation do not have the capability to communicate required status parameters.

NASA has sponsored a number of advanced technology studies in this general problem area. In 1970, for example, the General Electric Company investigated the overall problem of future space program mechanical readiness assessment and found that approximately 20,000 mechanical devices will be used on each space program comparable in size to the Saturn Program. It was concluded that full implementation of existing operational state-of-the-art instrumentation could provide only 70 percent of the needed readiness assessment capability. A survey of research laboratory checkout techniques identified Structure Borne Acoustics (SBA) as a non-destructive test technique having significant potential for improving readiness assessment and performance monitoring of mechanical systems.

1.3 STUDY OBJECTIVE

The objective of this study was to pursue the development of structure borne acoustic technology and to answer the following question: Is it practically feasible to implement structure borne acoustics on future space programs? Secondary tasks were to provide a structure borne acoustic handbook to aid system designers in the implementation process and to detail recommendations including cost and schedule estimates, for an orderly implementation of this technique into Kennedy Space Center mechanical systems.

A plan was prepared to provide for a systematic completion of study objectives. The work was divided into the following three task areas:

a. Task I —Selection and Analytical Description of Mechanical Components and Design of Acoustic Tests
b. Task II —Structure Borne Acoustics Testing
c. Task III—Test Data Analysis and General Solution Methodology Handbook

The sequence of task accomplishments and a breakdown of task elements are shown in Figure 1-1, Mechanical Readiness Assessment (MRA) Study Flow Chart.

A mid-term study progress report, DB72-A015, was published February 4, 1972, and should be referenced for detailed data concerning TASKS I and II study results. Appendix A documents contract performance schedules for all study tasks.

The text of this final report is presented in summary form to enhance readability. Whenever possible, backup data is relegated to the appendices which should be referenced for detailed information supporting statements and conclusions embodied in the report.

1.5 STRUCTURE BORNE ACOUSTICS—A NON-DESTRUCTIVE TEST TECHNIQUE

To achieve high and predictable reliability for a mechanical system, it is not sufficient just to build it from high quality components. Many defects may be initiated first during assembly or during subsequent tests. Such defects, which are not connected to component quality, reduce the overall system reliability. High reliability is also only a partial solution of the problem. What is really desired is high availability, i.e., short total down-time for maintenance or repair as compared to effective operating time. There are two general areas, final component or system checkout and early fault detection, where effective diagnostic and readiness assessment techniques can significantly increase total availability. In both cases the central problem is to evaluate internal conditions through external measurements, without disturbing the normal operation of the tested equipment. Obviously, external detection of internal defects presents new problems compared to conventional component testing and inspection. This is particularly true for mechanical defects. Internal cracks, loose bolts, worn bearings, etc., are no longer open for visual inspection or direct measurement; therefore, an information carrier is needed to transmit the internal information to the external evaluator.

Sound and vibration are excellent information carriers in mechanical structures. The fundamental mechanical events which occur in operating mechanical devices, such as rolling, sliding, impacts, etc., all produce sound, which tells the experienced listener much about the internal condition.

The total nondestructive evaluation or test technique for assessing the status of a mechanical device includes the method of stimulating the device, the response resulting
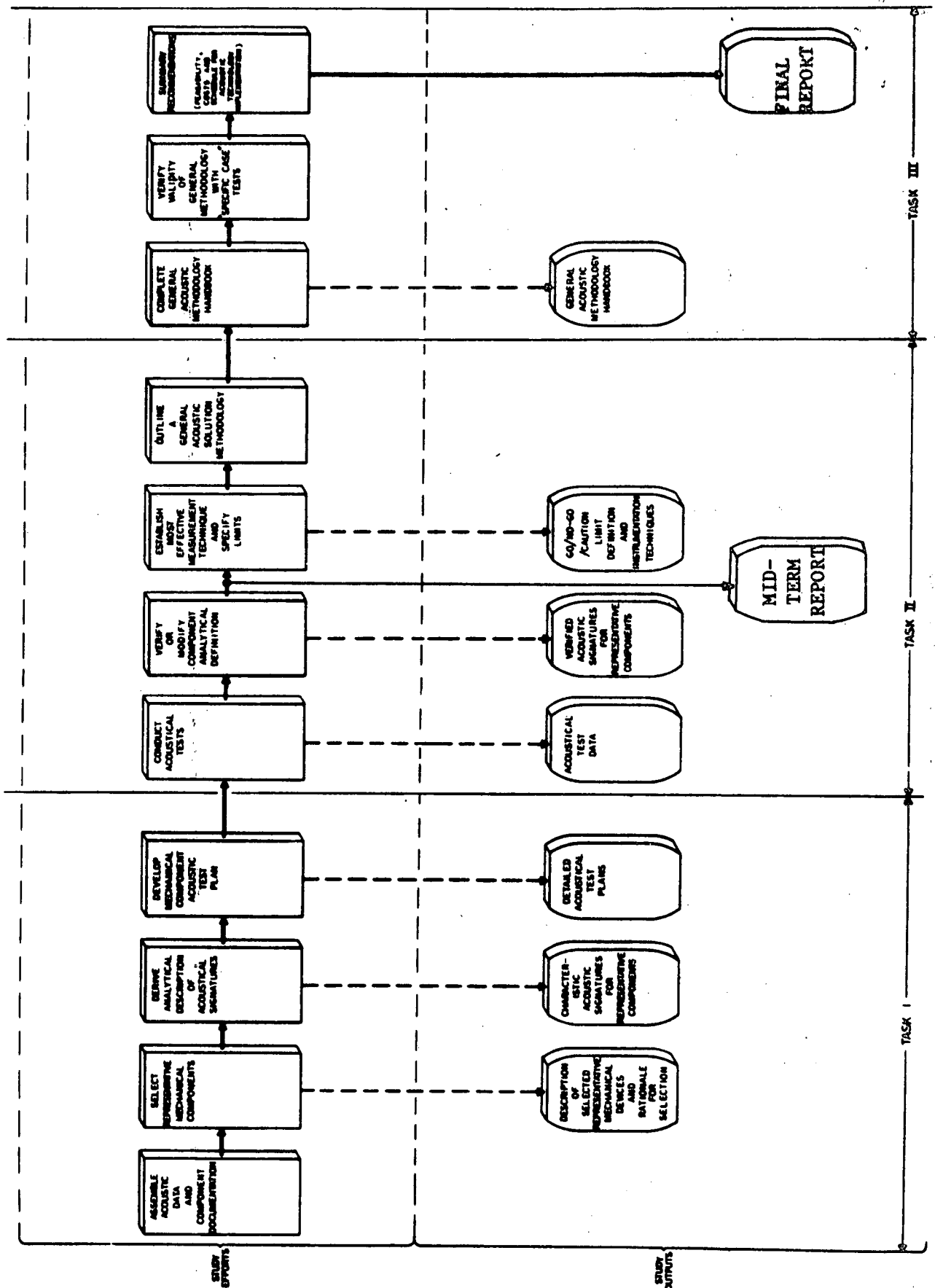
Figure 1-1. Mechanical Readiness Assessment (MRA) Study Flow Chart

from the stimulation, the transducer for communicating the response, and the hardware and software used for data processing and evaluation. The definition of "Structure Borne Acoustics" as used in this report includes all of these elements of a nondestructive test technique. It includes detecting and converting mechanical device noise into an electrical signal which is then processed, interpreted, and presented in such a form to provide go, no-go, or caution status of the mechanical device. Figure 1-2 pictorially illustrates this interrelationship.
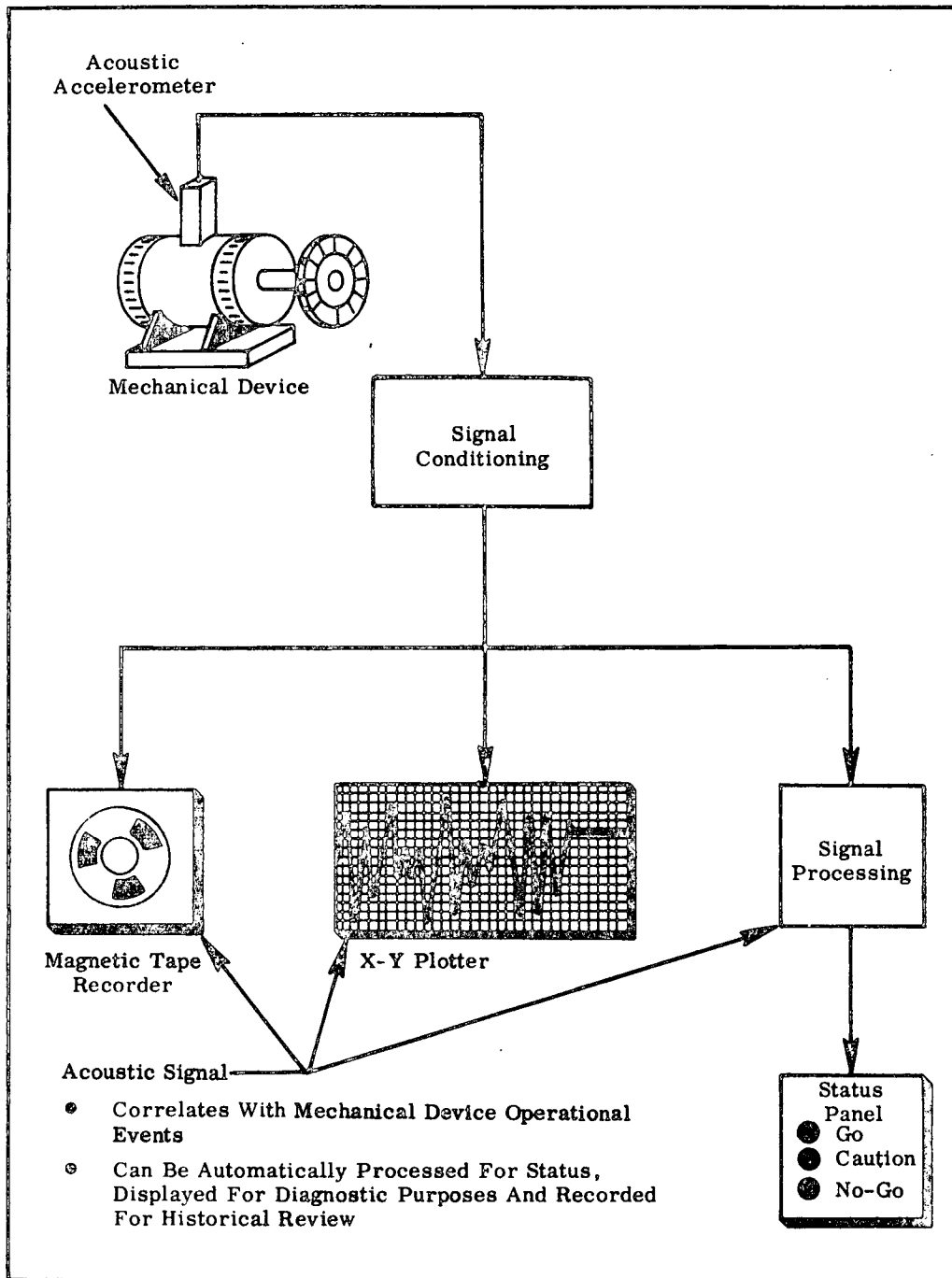
Figure 1-2. Structure Borne Acoustics Interrelationship

SECTION II

MECHANICAL COMPONENT ANALYSIS

2.1 GENERAL

Maximum component testing and data analysis efficiency requires considerable insight into the functional operation of the mechanical component, the testing routine, and the processing of acoustic data. During this study, five representative mechanical components were subjected to structure borne acoustic (SBA) testing. This section deals with the component analysis process which was developed and is essential for optimizing the test data acquisition and processing.

2.2 MECHANICAL TEST COMPONENT SELECTION

Test components were selected primarily on the basis of the following considerations:

    a. Component Acoustical Characteristics:
        (1) Single transient or transient action, e.g., solenoid valve.
        (2) Flow noise generator, e.g., pressure regulator.
        (3) Cyclic action, e.g., air motor.
    b. Component Availability and Configuration.
    c. Adequacy of Other Readiness Assessment Techniques.

The five components selected for structure borne acoustics testing include:

    a. Transient Action—A three-way, two-position, normally open, magnetically operated solenoid valve, 75M08825-3, manufactured by Marotta Valve Company.
    b. Flow Noise Generator—A three-way, spring-referenced, preset pressure regulator, 75M08831-1, manufactured by Marotta Valve Company.
    c. Cyclic Action—An axial piston, reversible air motor, 70A-66, manufactured by Gardner-Denver Company.
    d. Cyclic Action—A three-phase, 200-volt, 400-Hz, fractional horsepower blower, manufactured by Rotron, Inc.
    e. Cyclic Action—A 220/440-volt, 60-Hz, 1725 rpm induction motor driving a 1.5 kw generator, both manufactured by General Electric.

These five components are shown below in Figure 2-1.
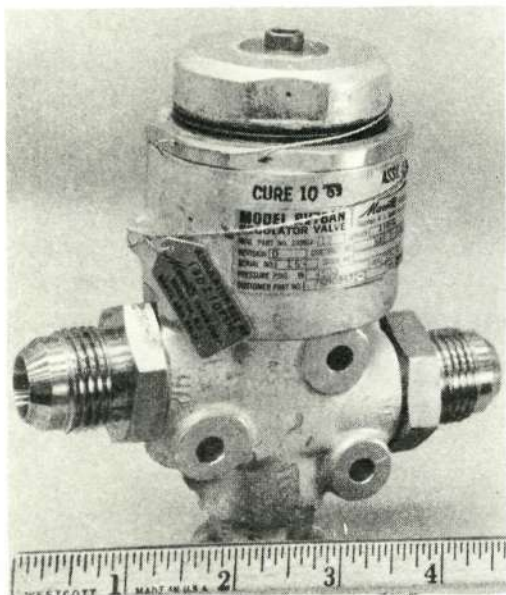
Pressure Regulator
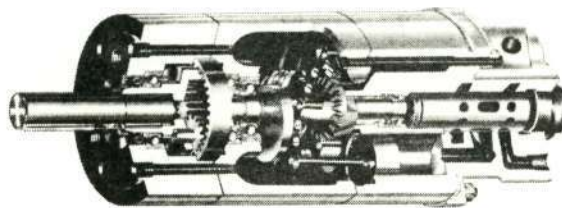
Air Motor
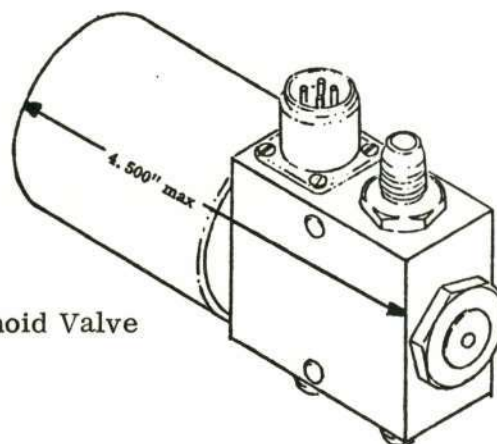
Solenoid Valve
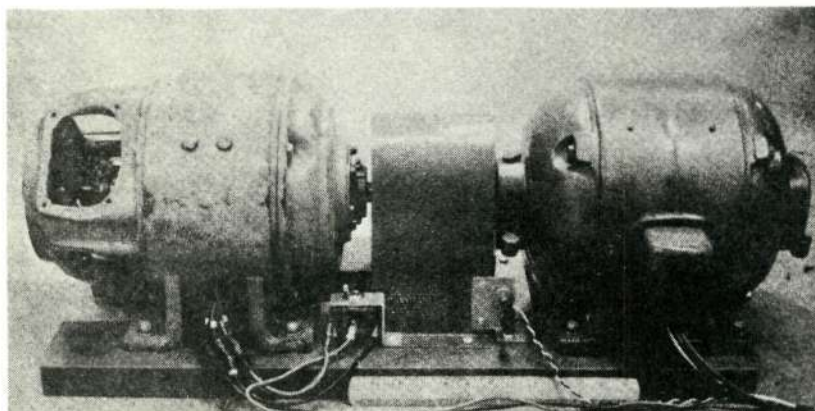
Motor Generator
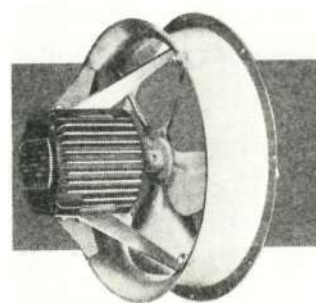
Blower

Figure 2-1. Components for SBA Testing

2.3 MECHANICAL COMPONENT ANALYSIS

Each selected component was analyzed in order to:

a. Understand the operating mechanics of the device.
b. Identify the internal noise producing reactions for normal and malfunctioning components.
c. Identify those component operational characteristics which can be correlated with component Go, Caution, and No-Go operation where, by definition:
    (1) Go—Fully operational.
    (2) Caution—Operationally adequate, degradation detected or suspected.
    (3) No-Go—Cannot meet operational requirements.
d. Select data processing technique(s) having the best probability of displaying the component operational characteristics.

The analysis process developed for this study employs the following steps:

a. Acquire and analyze documentation for selected component.
b. Identify normal operation noise sources—flow, impacts, resonances.
c. Construct a failure mode tree—identifies failure modes, effects.
d. Predict normal signature—RMS amplitude versus time.
e. Assess impact of failure modes on normal acoustic signature.
f. Predict failure mode signatures.

2.3.1 COMPONENT DESCRIPTION/OPERATIONAL ANALYSIS

A thorough understanding of the component operating characteristics is necessary in order to interpret the acoustic signature obtained. Source data found useful for component evaluation and analysis are available as:

a. Design Documentation—Drawings, Specifications, and Vendor Literature.
b. Operations and Maintenance Manuals, Procedures.
c. Reliability Data— Failure Reports, Failure Mode and Effects Analyses.

Based on the above literature, the five selected components were analyzed to establish the physical or mechanical interactions taking place within the component during normal operation. It is these interactions which produce the component's composite acoustic signature.

2.3.2 RELIABILITY ANALYSIS

Having thus become familiar with the component's principles of normal operations and having identified the internal noise producing events, it is then appropriate to identify the potential failure modes for the component. This process was accomplished through review of failure reporting documentation and engineering analysis and was documented in the form of a failure mode tree. Figure 2-2 is a sample failure mode tree for the 70A-66 air motor which illustrates the approach. The uppermost block(s) of the tree describe the operational effect, i.e., No-Go or Caution, expected due to the failure modes identified in the second row. The failure mechanism identifies the failed piece-part and the specific problem. The bottom row provides explanations for the identified failure mechanisms.
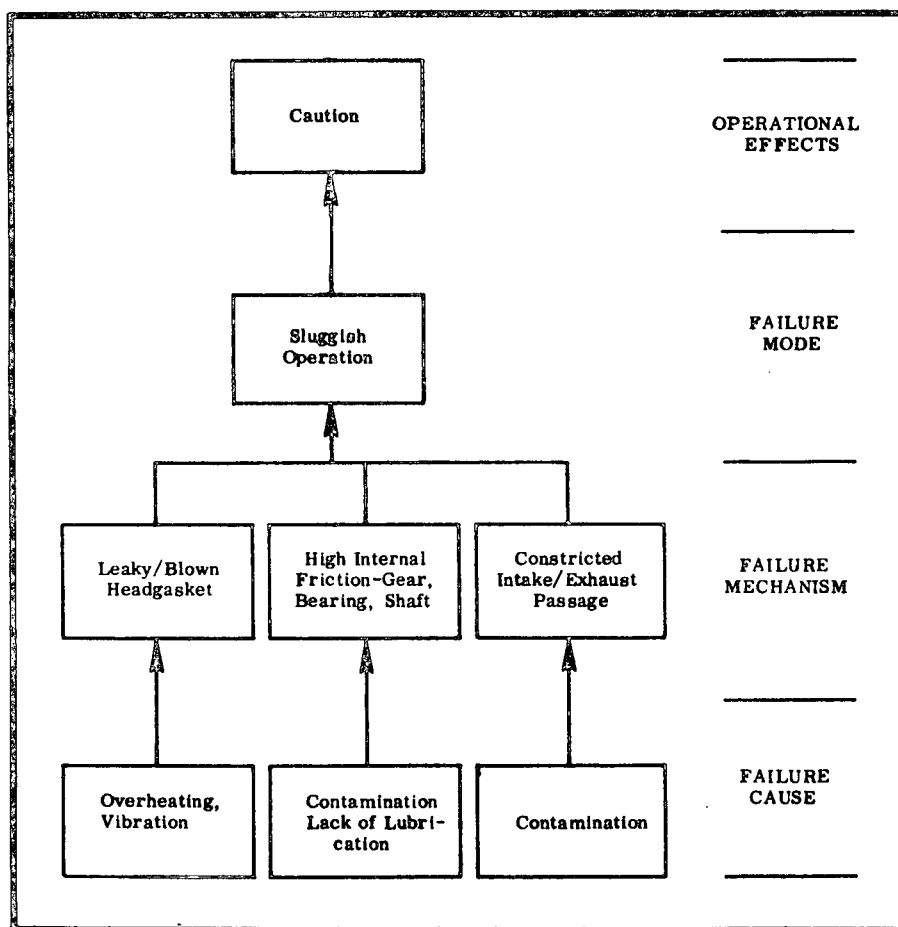
Figure 2-2. Sample Failure Mode Tree

2.3.3 ACOUSTIC SIGNATURE MODEL

Subjective acoustic signatures were predicted on the basis of physical and mechanical events taking place within the representative components. This was accomplished through examination of the relative timing of each event and estimating the relative acoustic amplitude. The prediction is displayed by relative RMS amplitude versus time. Figure 2-3 is an illustrative sample and is the predicted signature for the 70A-66 air motor.

Mathematical analysis of cyclic component operation is necessary in order to provide:

    a.   A time or event base for relating noise producing reactions within the component.

    b.   Preliminary determination of filter frequencies which will allow display of specific aspects of component operation, e.g., a gear mesh frequency.

Computer programs exist which predict frequencies and relative amplitudes for good and defective ball bearings.

Notes:
1. Piston sliding noise, background, gears and bearings.
2. Piston direction reversal and intake air surge.
3. Piston direction reversal.
4. Exhaust air surge.
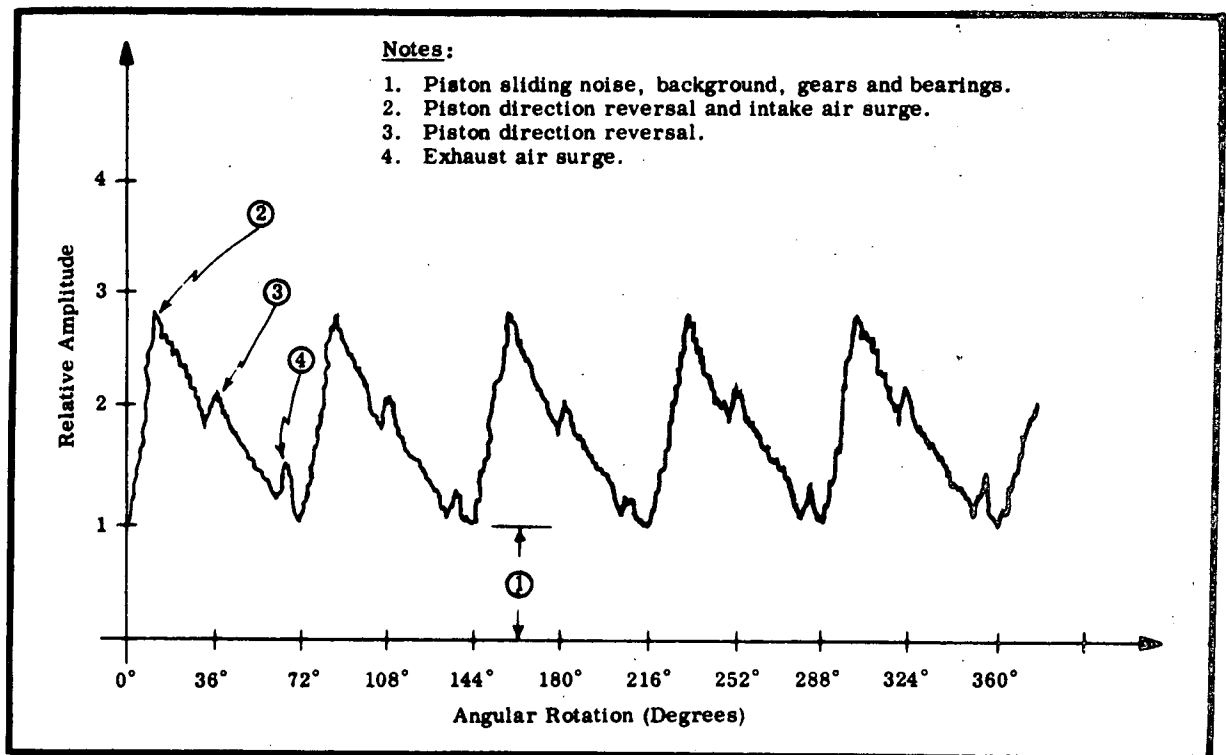
Figure 2-3. Air Motor Predicted Signature Envelope

Note that the coincidence of several internal events produces the greatest signal amplitude. The angular rotation in degrees refers to the internal pinion gear, not the output shaft. (For information on the air motor see Appendix B3.) The correlation between the predicted air motor signature and that of Figure 2-4 obtained during acoustic testing is unmistakable.
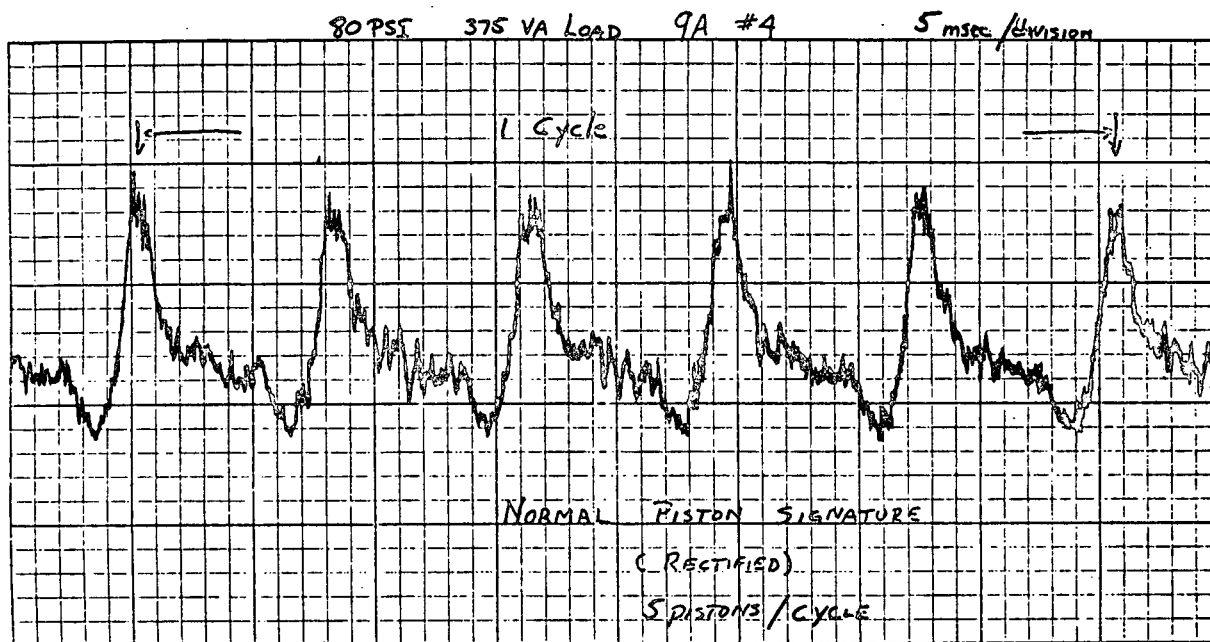
Figure 2-4. Normal Piston Signature (Rectified) (5 Pistons/Cycle)

To deduce the acoustic signature for a component containing a given failure mode, it is necessary to evaluate the effect of that failure mode on all component noise sources. This can best be accomplished through a failure mode/acoustic element matrix, a sample of which is shown in Table 2-1.

Table 2-1

Air Motor Failure Mode/Acoustic Element Matrix

Air Motor 70A-66		Bearing	Gear	Intake/Discharge Air	Piston	Internal Air Leakage
Failure Mode	Failure Mechanism					
Sluggish Operation	Leaky, Blown Head Gasket	A	A	A	A	A
	High Internal Friction - Gear, Bearing, Shaft	A	A	N	N	A
	Constricted Intake/ Exhaust Passage	N	N	A	N	A

N—Normal
A—Abnormal
O—None

2-6

Note that the failure mode and mechanisms for this sample are those illustrated in Figure 2-2. Sluggish operation in this case includes erratic angular velocity as well as reduced rpm depending upon the failure mechanisms. Figure 2-5 displays both of these effects.
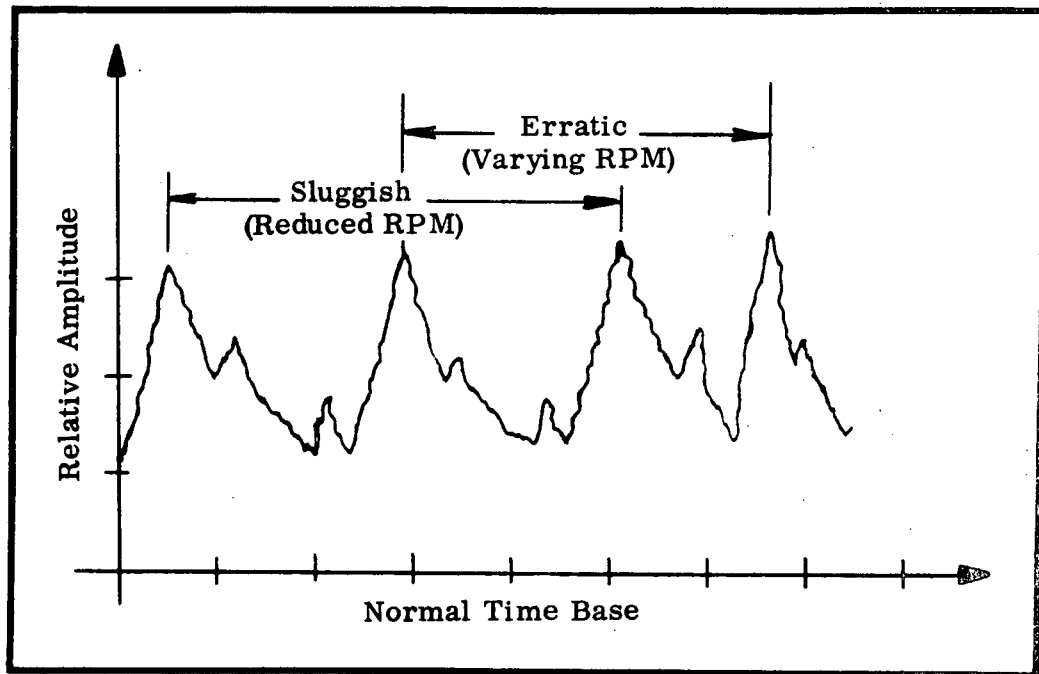
Figure 2-5. Failure Mode Effect Upon Air Motor Signature

Detection of reduced or varying rpm is accomplished through peak-to-peak time measurments compared with those of a standard. A consistent discrepancy would indicate reduced rpm. A varying time difference indicates an erratic radial velocity within one revolution.

The component analysis routine described has, as a tangible end product, the predicted acoustic signature envelope for good and malfunctioning components and provides the designer/analyst with a knowledge of component operation which facilitates correlation of the acoustic test data with the internal interactions which produced the acoustic signal. The comparison of predicted acoustic signature versus that actually obtained and the resolution of discrepancies provides a firm basis for a more accurate analysis of succeeding components.

SECTION III

STRUCTURE BORNE ACOUSTIC TEST DISCUSSION

3.1 GENERAL

In this section, a brief description of the test program and test facilities is presented. The test results for each of the five components are summarized, and the interpretation of acoustic data is discussed.

A statistical approach was employed both for planning tests and evaluating significance of test data. Having established that:

a. The data distributions for defective and non-defective components are normal.

b. The variance for defective components does not differ significantly from that of non-defectives.

c. The mean for defective components differs significantly from that of non-defectives.

Limits for defective and non-defective components were established at the 90-percent confidence level. This takes the form shown in Figure 3-1.
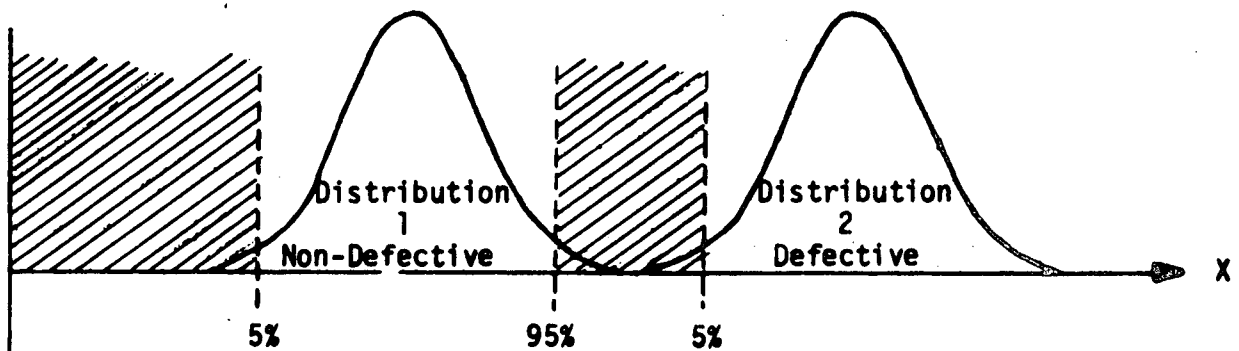
Figure 3-1. Non-Defective versus Defective Distributions

In the case depicted, those values of x between the 5-percent and 95-percent points of distribution 1 are considered normal operation. Values of x to the right of the 5-percent point of distribution 2 are considered a failure. The shaded areas indicate that an anomaly exists, but the performance of the mechanical device has not deteriorated to the point where a failure has occurred.

3.2 TEST FLOW

A general test methodology was developed and has applicability to each SBA test sequence. For each component tested, there is a fixed pattern of activities requiring completion. These activities and their sequences are shown in the Test Flow diagram, Figure 3-2.
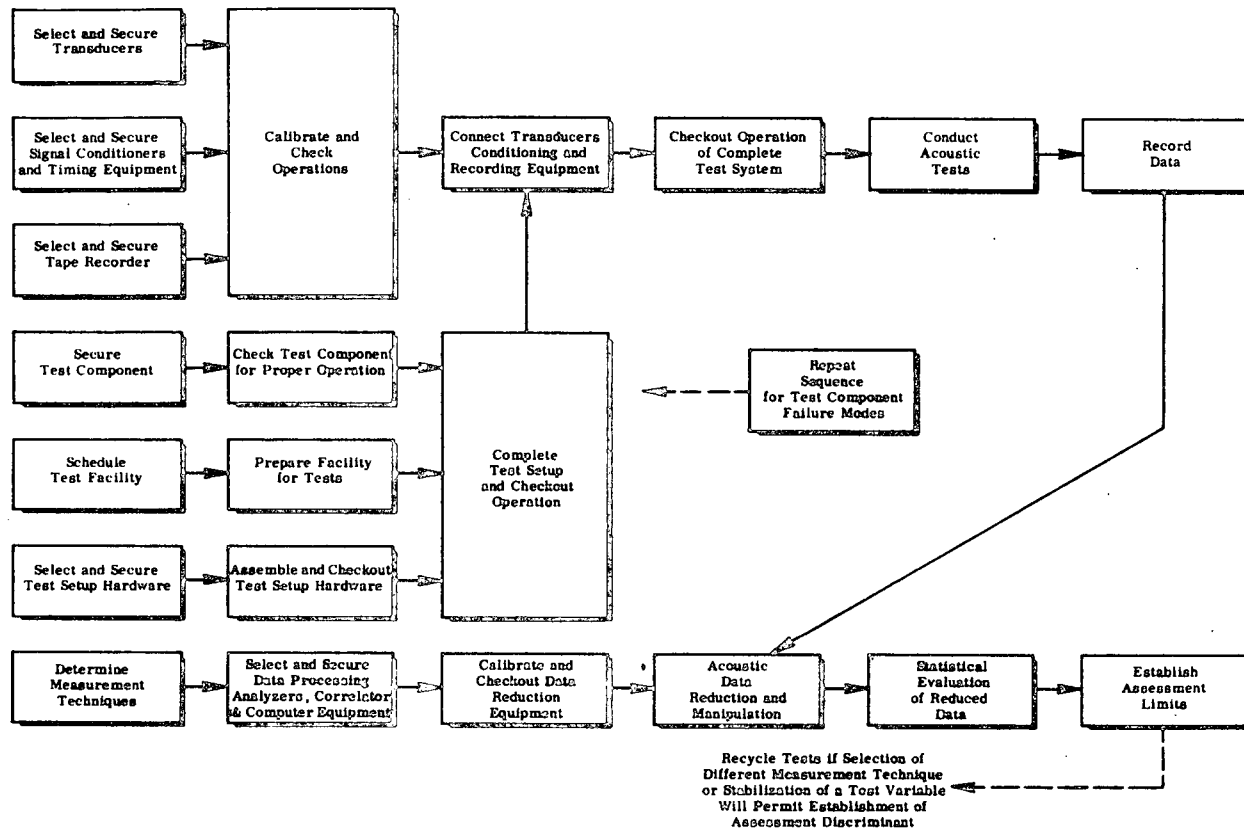
Figure 3-2. Structure Borne Acoustic Test Flow Diagram

3.3 TEST FACILITIES

Test facilities at General Electric's Research and Development Laboratory, Schenectady, New York, were employed for this test program. A special facility test set-up was designed and built by General Electric as a means of study in the acoustic signatures of the mechanical components under simulated operating conditions. This test set-up, see Figure 3-3, provided for ready installation and quick replacement of the test components.

General Electric Spectrum Analysis Facility Figure 3-4 and Summation Analysis Facility Figure 3-5 were used for data reduction and analysis.
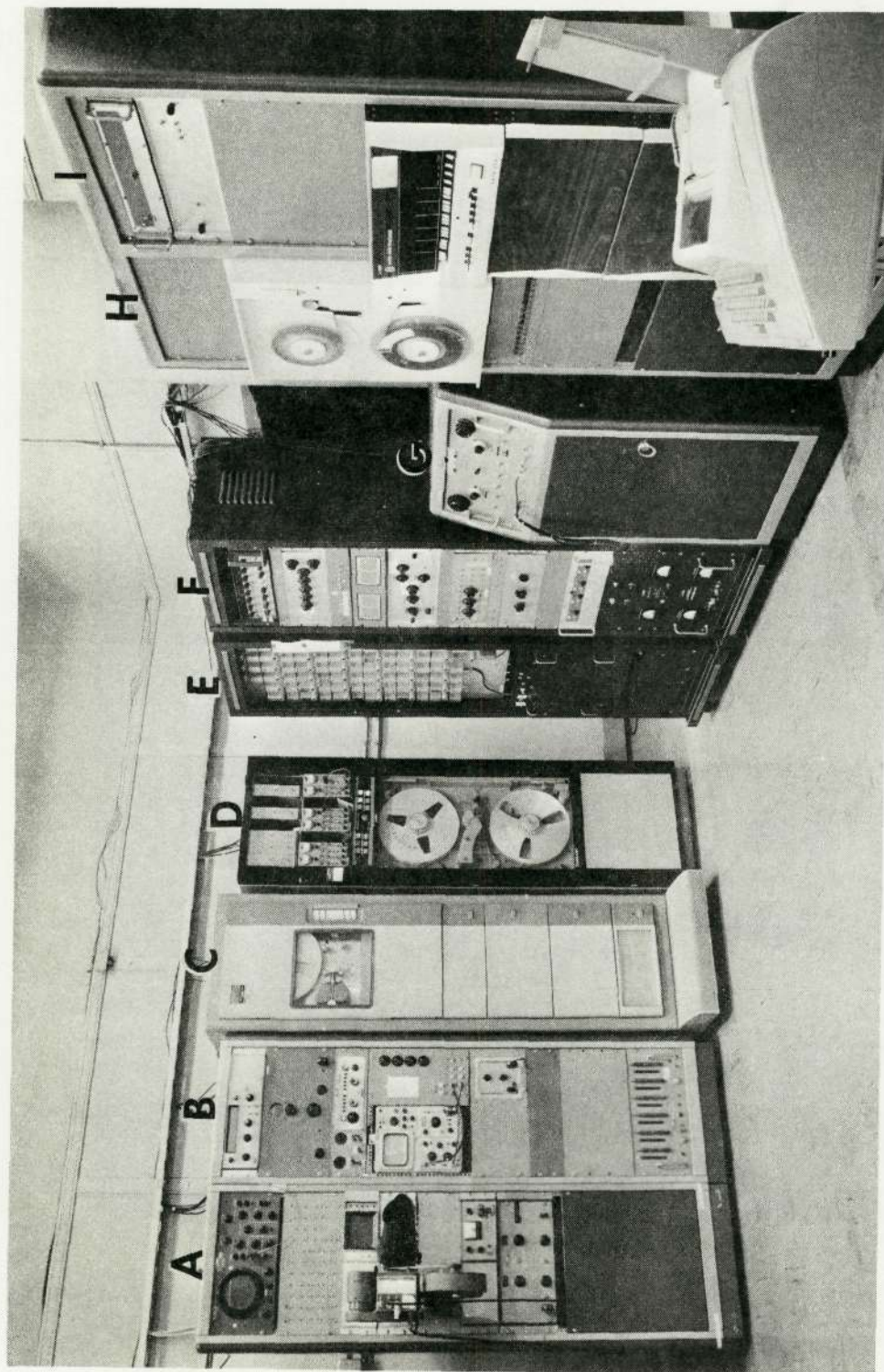
Solenoid Valve
75M08825

Regulator
75M08831

Magnetic
Tape Recorder

Figure 3-3. Test Setup

A 35mm Recording Camera and Film Processor
   Allen Dumont 304-AR and Auxilliary Equipment
B Oscilloscope and Auxilliary Equipment
C Analogue Magnetic Tape Recorder
D Analogue Magnetic Tape Recorder Sangamo 4700

E R&D Center Frequency Analyzer (80 Filters)
F Spectrum Analysis Power Supplies/Misc Equipment
G R&D Center Frequency Analyzer (200 Filters)
H Digital Magnetic Tape Recorder
I Varian 620i Minicomputer Rack

Figure 3-4. Spectrum Pattern Analysis Facility
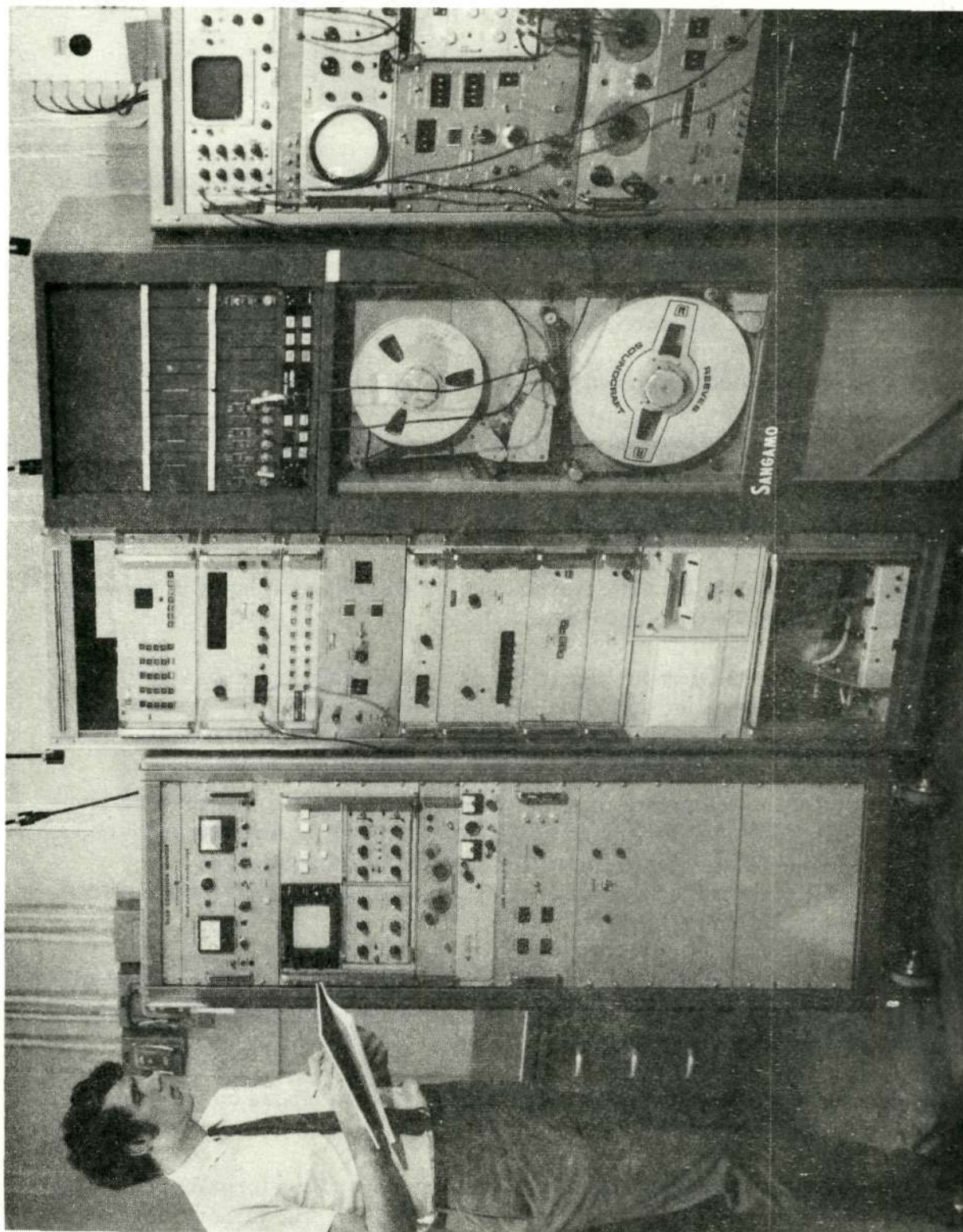
Figure 3-5. Summation Analysis Facility

3.4 COMPONENT TEST DISCUSSION

3.4.1 SOLENOID VALVE—75M08825-3

3.4.1.1 Test Result Summary

Five different solenoid valves were tested in normal and inserted defect configuration. Results showed that:

a. Repetitive operations of each valve were very consistent in the time domain.

b. The acoustic signature can be correlated with events taking place within the valves.

c. Inserted defects produced a measurable variation in the acoustic signature.

d. Care must be exercised in the insertion of defects to preclude biasing the data.

3.4.1.2 Acoustic Data Interpretation

Figure 3-6 contains composite acoustic waveforms for the actuation cycle of solenoid valve 75M08825-3. Shown on the Figure are:

a. Signal A is an acoustic signature with valve actuation at 28 volts, no pressurization, no GN_2 flow, and normal operation.

b. Signal B is an acoustic signature with valve actuation at 28 volts, 1000 psig, GN_2 flow (≈ 30 milliseconds), and normal operation.

c. Signal C is a signature of valve actuation at 28 volts, no pressurization, no GN_2 flow, and simulated sluggish operation. Spring was tightened to increase force opposing actuation direction by 6 pounds.

d. Signal D is signature of valve actuation at 18 volts input, no pressurization or GN_2 flow.

It should be noted that these signatures are each representative of over 30 individual operations. Relative amplitudes are specified on the waveform graph, and the time base is from solenoid voltage application.

From comparison of these waveforms, the influence of failure modes on the acoustic signature timing is apparent.

A comparison of normal valve deactuation acoustic signature (Waveform A) and a failure mode signature (Waveform B) is presented in Figure 3-7. The failure mode signature was simulated by increasing force opposing actuation direction. These signals clearly show that limit switch indicating valve action triggers 3 to 5 milliseconds before the stem actually slams against the valve housing seat to complete deactuation.
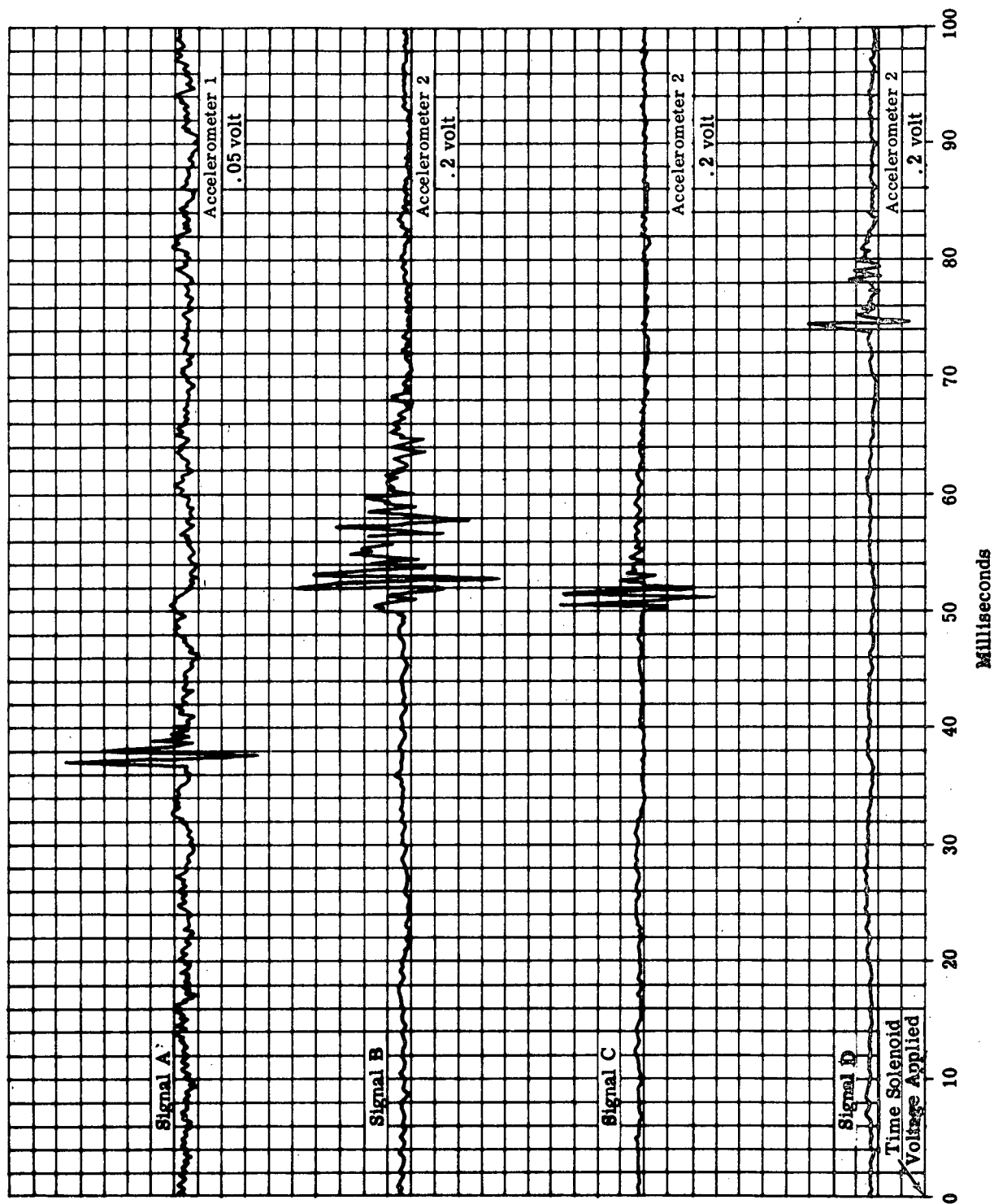
Figure 3-6. Solenoid Valve Actuation Acoustic Signatures

ρ
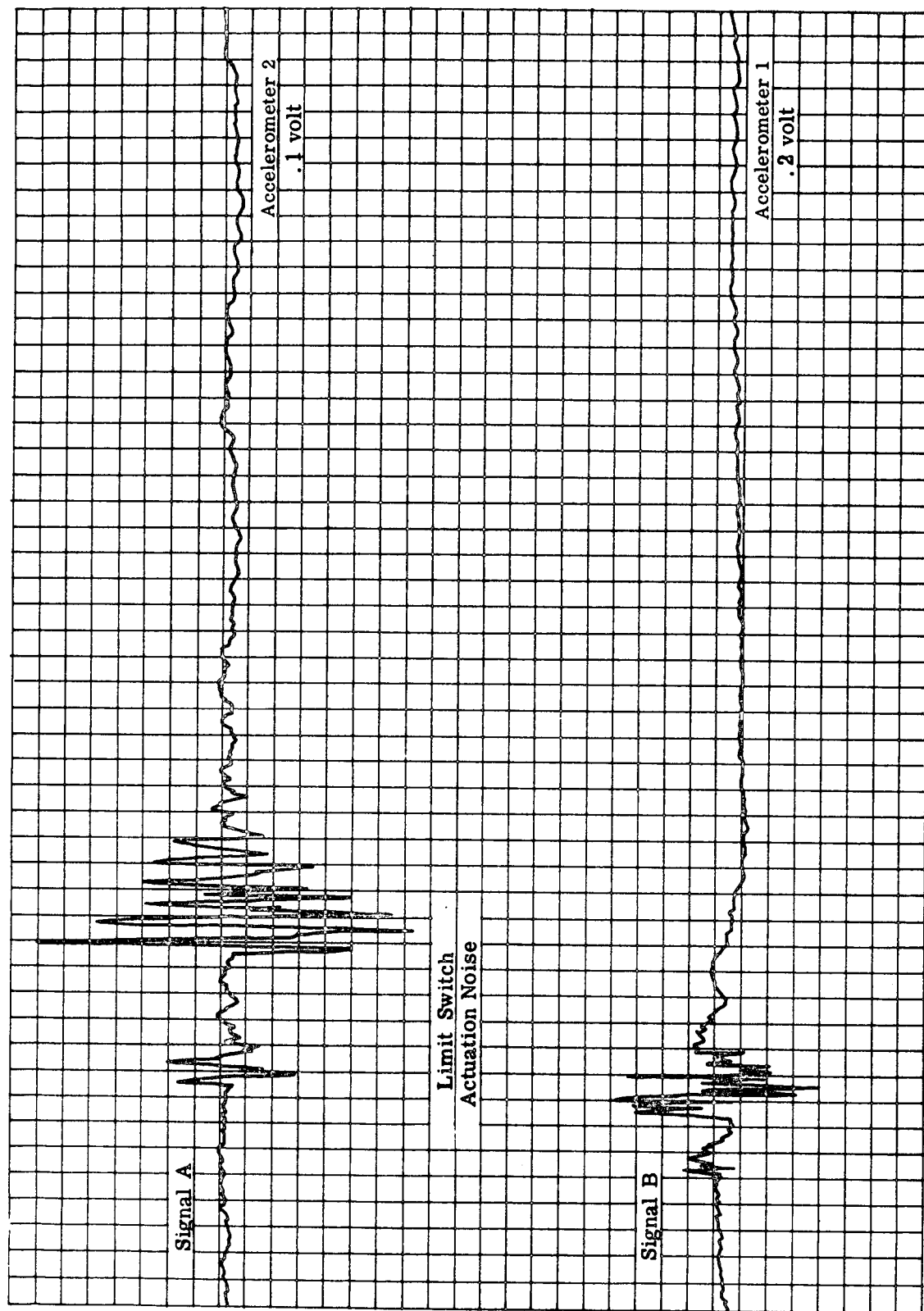
Figure 3-7. Solenoid Valve Deactuation Acoustic Signatures

The real-time frequency analysis, Figure 3-8, display of valve actuation and deactuation shows the frequencies excited by the impact transient. The plots are three-dimensional in the sense that they provide time (x axis), frequency (y axis), and amplitude information. The display range is 48,000 Hertz. The time base is 27.6 inches per second or 36 milliseconds per inch. Amplitude is displayed on a relative basis as indicated by the intensity modulation of the frequency scans. The trace at the bottom of each spectrogram is solenoid voltage and correlates the frequency data with valve operational events. The strongest frequency component is found at 11K Hertz and results from valve body resonance due to stem and seat contact.

The probability density functions of comparative normal and failure mode valve actuation and deactuation times are illustrated on Figure 3-9 in histogram form. Failure mode operations were simulated by setting valve spring tension to increase force opposing actuation direction by 13 pounds. The operating time distributions C and D for failure mode versus normal actuation show no overlap for approximately 60 total operations. Similar results were obtained for deactuation times. These histograms indicate: (1) the stability of valve operating times, (2) variance relates directly to performance, and (3) the failure mode signatures are significantly different from those of normal operations. Thus, acoustic go, no-go, and caution limits can be established.

3.4.2 PRESSURE REGULATOR—75M08831-3

3.4.2.1 Test Result Summary

Data was acquired on the pressure regulator from one accelerometer on the housing and one pressure transducer in the regulated line. While correlation was obtained between the RMS value of the flow noise amplitude and the pressure to the regulator, the absence of noise producing interactions within the regulator reduces SBA to flow noise detection. At any given point in time, normal regulator flow can vary between zero and full flow depending upon the downstream pressure (which is a function of demand). Incipient failure or performance degradation of a regulator is frequently characterized by sluggish operation which can be determined by analysis of absolute downstream pressure and pressure rate of change. Therefore, the knowledge of downstream pressure is required for readiness assessment, thereby making SBA redundant.

SBA instrumentation used for testing purposes was sensitive to flows (or internal leakage) on the order of 4cc/minute. Discussions with KSC operations personnel indicate that leak detection to 1cc/minute or less would be beneficial. KSC is presently sponsoring an ongoing leak detection study, thus this investigation was not pursued further.

In consideration of the above, pressure regulator testing was terminated with the consensus that SBA currently has limited application to devices producing only flow noise.

Valve Deactuation

Valve Actuation

Frequency
(K Hertz)

48
40
32
24
16
8
0
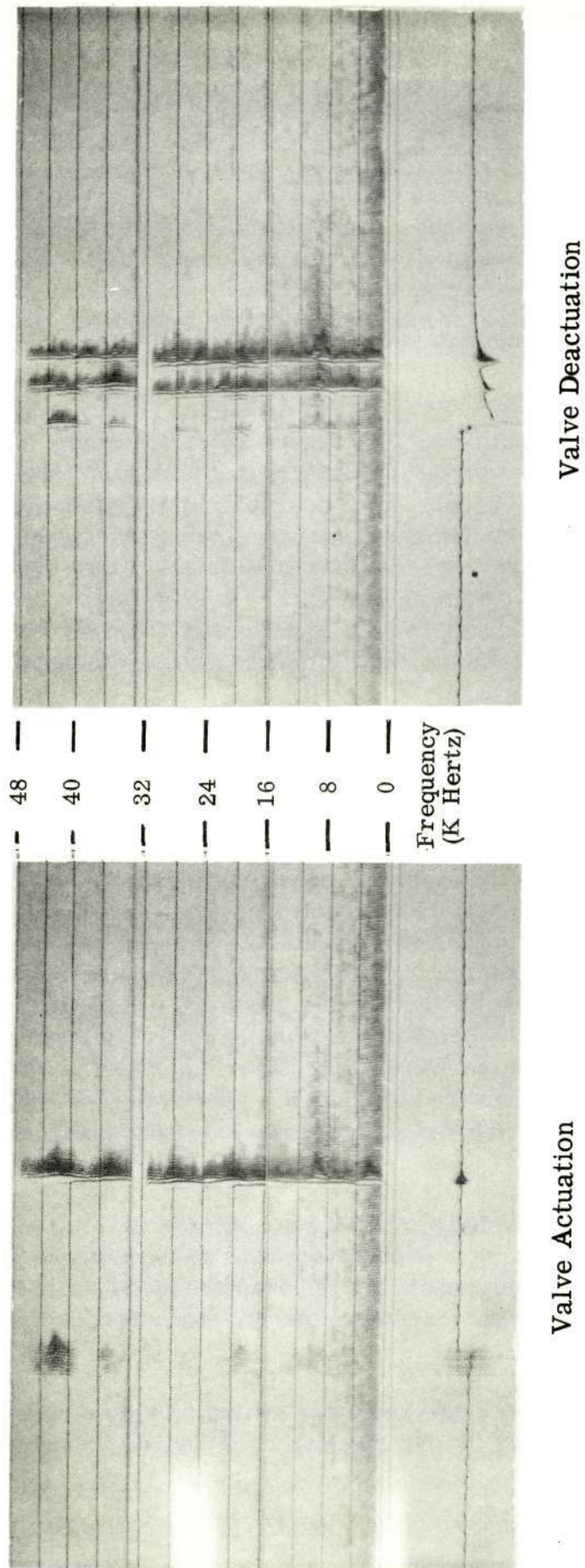
Figure 3-8. Modulated Spectrograms of Solenoid Valve Operation
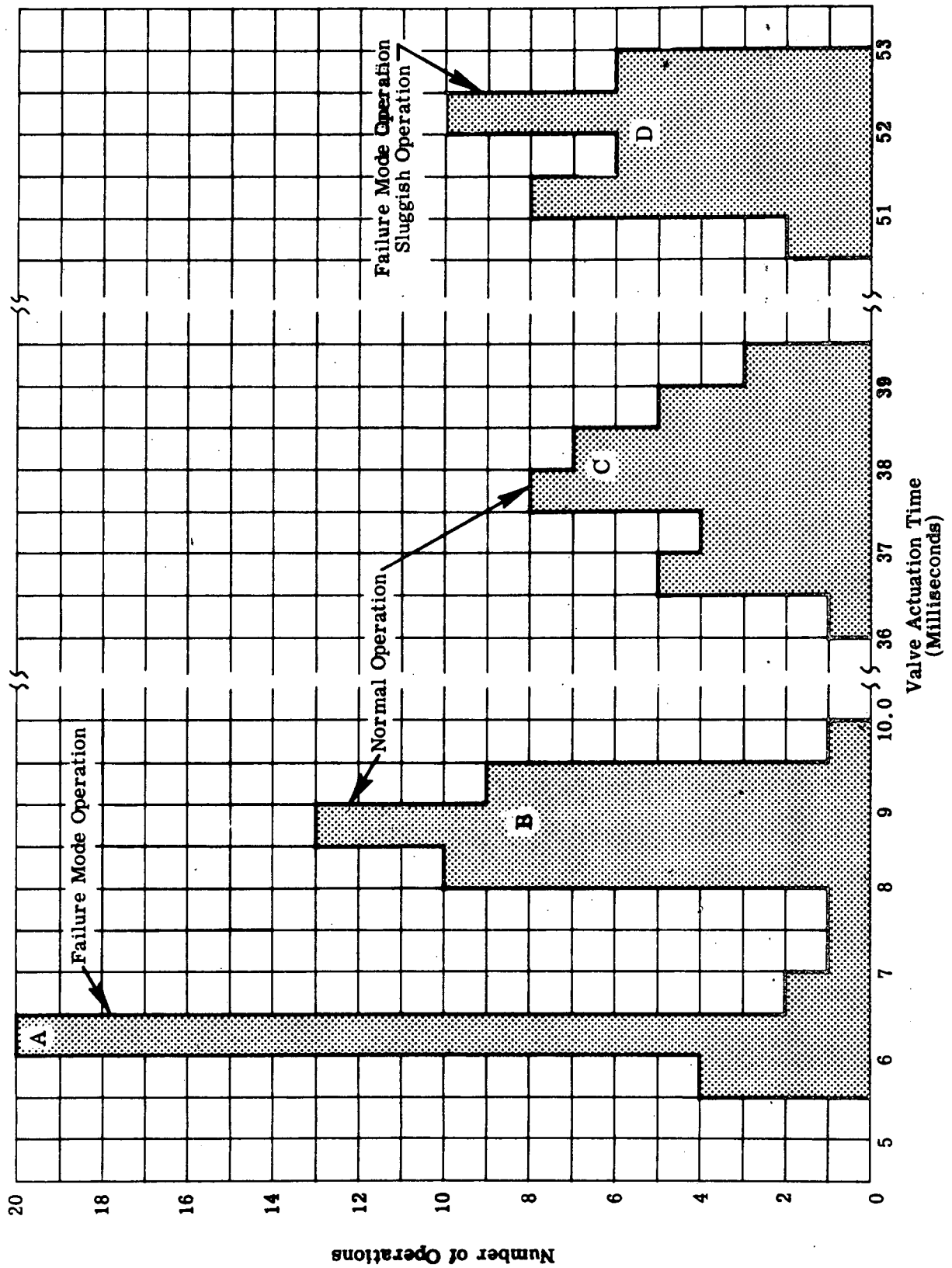
Figure 3-9. Histograms of Valve Operations

3.4.2.2 Acoustic Data Interpretation

On Figure 3-10 the top trace is the raw accelerometer signal; the bottom, that provided by a pressure transducer in the output or regulated line.

On Figure 3-11 the top trace is a negative RMS of the raw accelerometer, and again, the bottom trace is the pressure transducer output (regulator output pressure).

Note on both figures that the largest acoustic signal is obtained when the regulator relieves to a lower pressure. The next largest acoustic signal is due to normal regulator flow.

3.4.3 AIR MOTOR—GARDNER DENVER 70A-66

3.4.3.1 Test Result Summary

The air motor tests were conducted under simulated operational conditions. The motor was driven with a 80 psi air supply and loaded with a belt-driven, dc generator. The generator output was monitored to indicate load and to assure repeatability of test parameters. At the beginning of the test procedure, all motors to be used were run in the as-received condition, and test data was recorded on magnetic tape. Several defects were inserted in the motors, and data was recorded in the defective mode. All data analysis was performed on the magnetic recordings.

The structure borne acoustic data was obtained from three accelerometers mounted on the housing (see Appendix B3) along mutually perpendicular axes. A tachometer signal was obtained from the pulley wheel on the output shaft, and gave six pulses per revolution. The only preprocessing performed before recording was to amplify the accelerometer signals to that level required by the tape recorders.

The normal signature of the air motor consists of a broad-band noise signal combined with a number of discrete tones. The broad band noise results from the pulsations of air flow through the valves and cylinders of the motor. The discrete tones were identified through analysis of the motor to be gear-mesh frequencies, the piston frequency, bearing tones, and shaft imbalance component frequencies are tabulated below:

a.	Output Shaft Speed	4 rps	
b.	Piston—29 x 5.5	116 Hz	
c.	Ring Gear—48 x 5.5	192 Hz	
d.	Bearing Tones	17 Hz	Harmonics
e.	Bearing Tones	14.9 Hz	

Figure 3-10

Figure 3-11

RMS Noise Amplitude

Relative Pressure

← 217 PSi

← 197 PSi

3 PSi
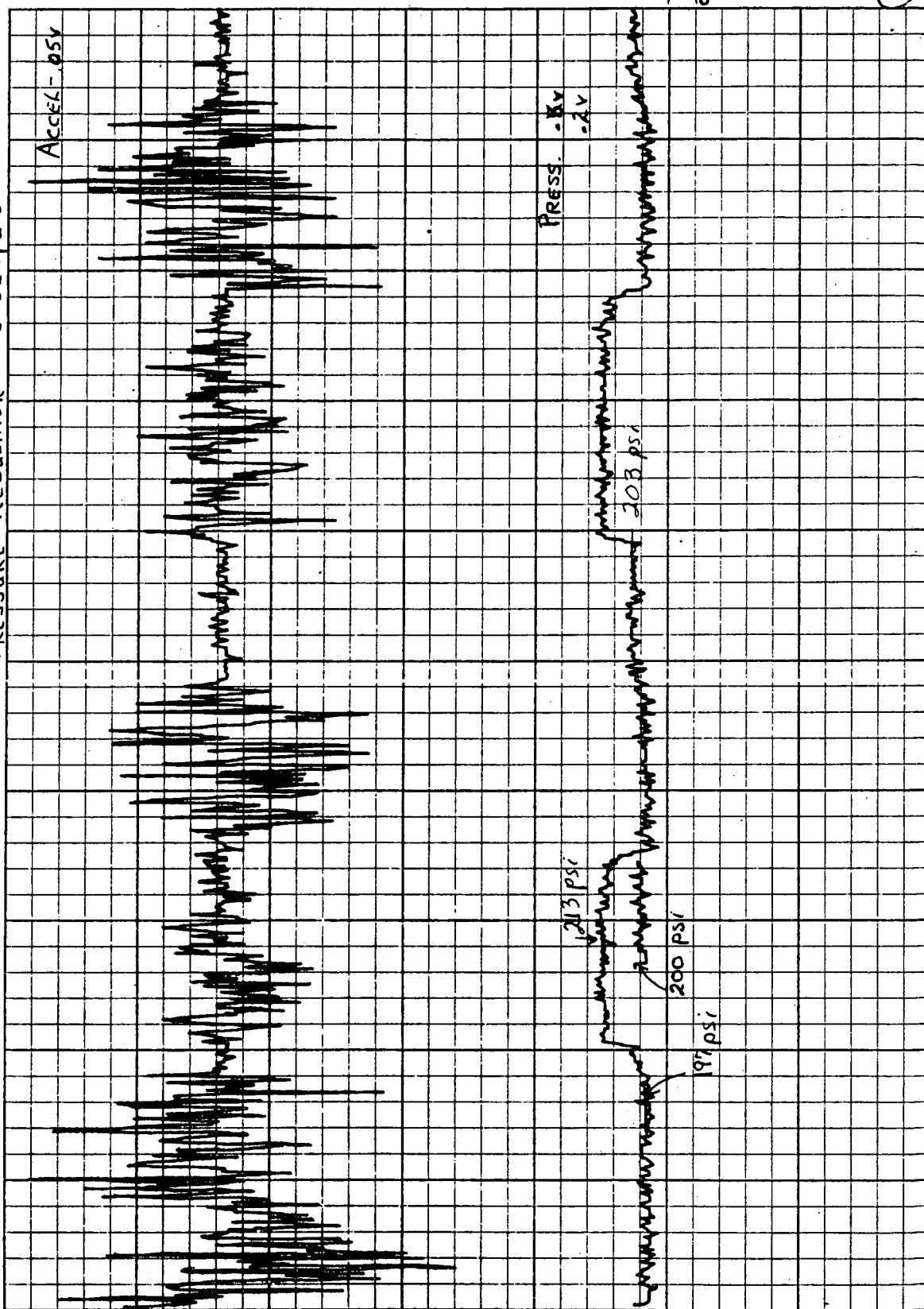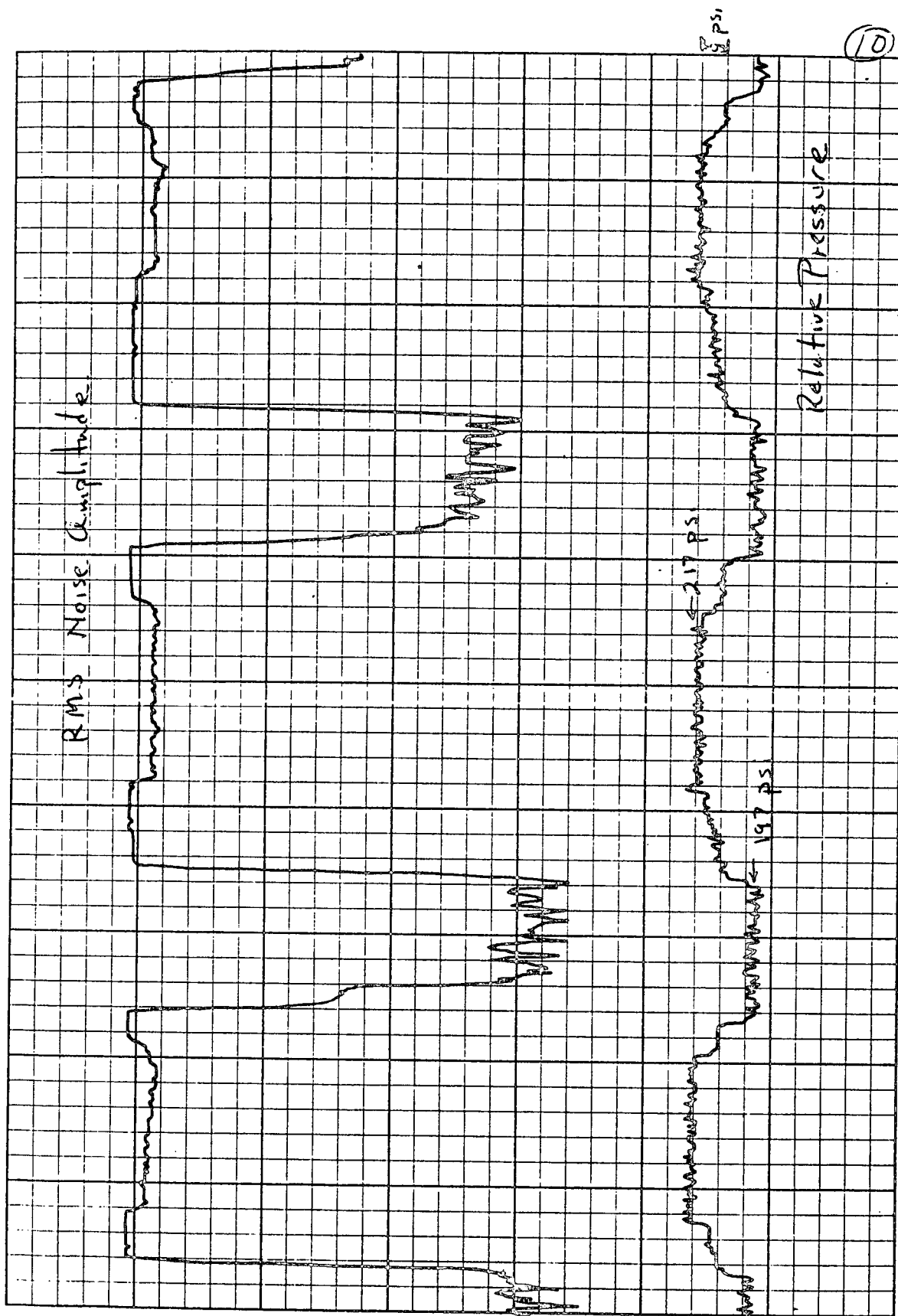
3.4.3.2   Acoustic Data Interpretation

Figure 3-12 illustrates two of the dominant tones generated in this case at a reduced air pressure of 20 psi and no load. The pistons excite the housing at 29 times the shaft speed, i.e., there are 29 piston cycles for every revolution of the output shaft. The ring gear, with the pinion and two associated planets, generates a meshing tone at 48 times per revolution. (There are 48 teeth on the ring gear.) In this Figure, these tones are related to the 6x per revolution tach signal, and derived through summation analysis.

Figure 3-13 shows the effect of a full load at 80 psi operating pressure. Most noticeable is the amplitude modulation on the gear tones at 10 times per revolution. This is the result of imbalance in the load-pulley system where a 10:1 pulley size reduction has been used to drive the loading generator at the required speed. The piston vibration data is tightly filtered about the predicted frequency. If instead the data is processed to enhance the pulsating broad-band noise generated by the air flow, Figure 3-14 results.

In this case, the data was rectified before processing and the filtering is adjusted to pass all the high frequencies (actual settings are not significant). Since the motor is of a five-cylinder design, five piston noise envelopes constitute one revolution of the piston swash plate. The chart shows five similarly shaped and equally spaced waveforms generated during the piston power cycles. In fact, at any given time, two pistons are opened to the 80 psi line pressure so that each envelope is a composite of two adjacent pistons.

Figure 3-15 shows the effect of introducing a defective head gasket to air motor SN 751685. A slot was cut in the gasket between two adjacent cylinders. The gap was approximately 1/4 inch. If the joined cylinders are labeled 1 and 2, and it is remembered that adjacent cylinders are pressurized simultaneously, then the chart can be easily understood. Two full revolutions or ten piston excursions are displayed. At the second major division cylinders 1 and 2 are pressurized simultaneously. They are joined by the valve so the defect has no effect. At the third division, 2 and 3 are pressurized but 2 leaks to exhaust through 1. At the fourth division, 3 and 4 are pressurized; and at the fifth division, 4 and 5 are pressurized but 1 and 2 are not involved. Then again at the sixth division, 5 and 1 are pressurized but 1 leaks to exhaust through 2. This pattern repeats every five divisions. The leaky head gasket can be clearly identified.

Possible external leakage due to misalignment of the head assembly or improper torqueing of the bolts is shown in Figure 3-16. This air motor (SN 573139) yielded these results as received for testing. The marked differences in amplitude indicate leakage on one side of the head.

Axial scoring of one cylinder wall introduced a waveform peak between the normal peaks (SN 573098) in Figure 3-17. Speed instability of the motor with respect to the analysis parameters causes the repetition of this new peak to be partially obscured, but its presence is still visible.

Figure 3-12

80 PSI 375VA OUTPUT LOAD

Tachometer (1x per revolution)

Piston Frequency
29x per revolution
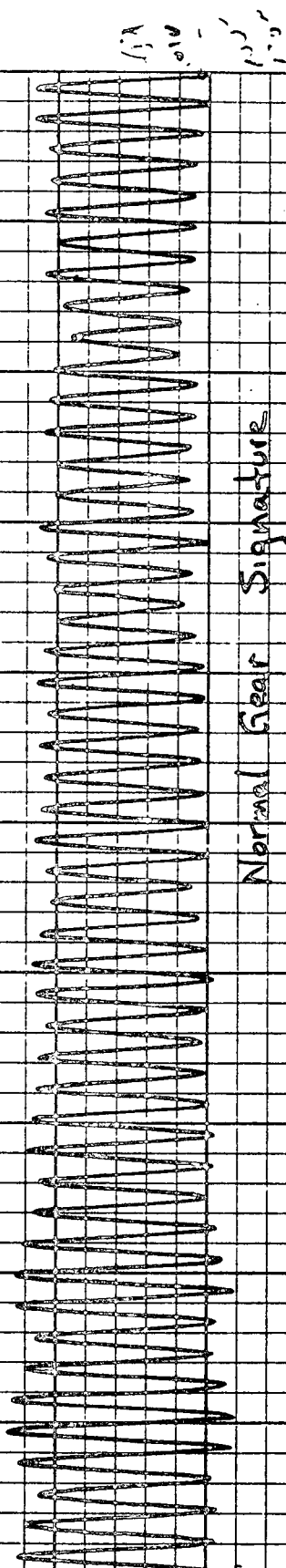
Gear Mesh Frequency
48 x per revolution - modulated 10z/rev.
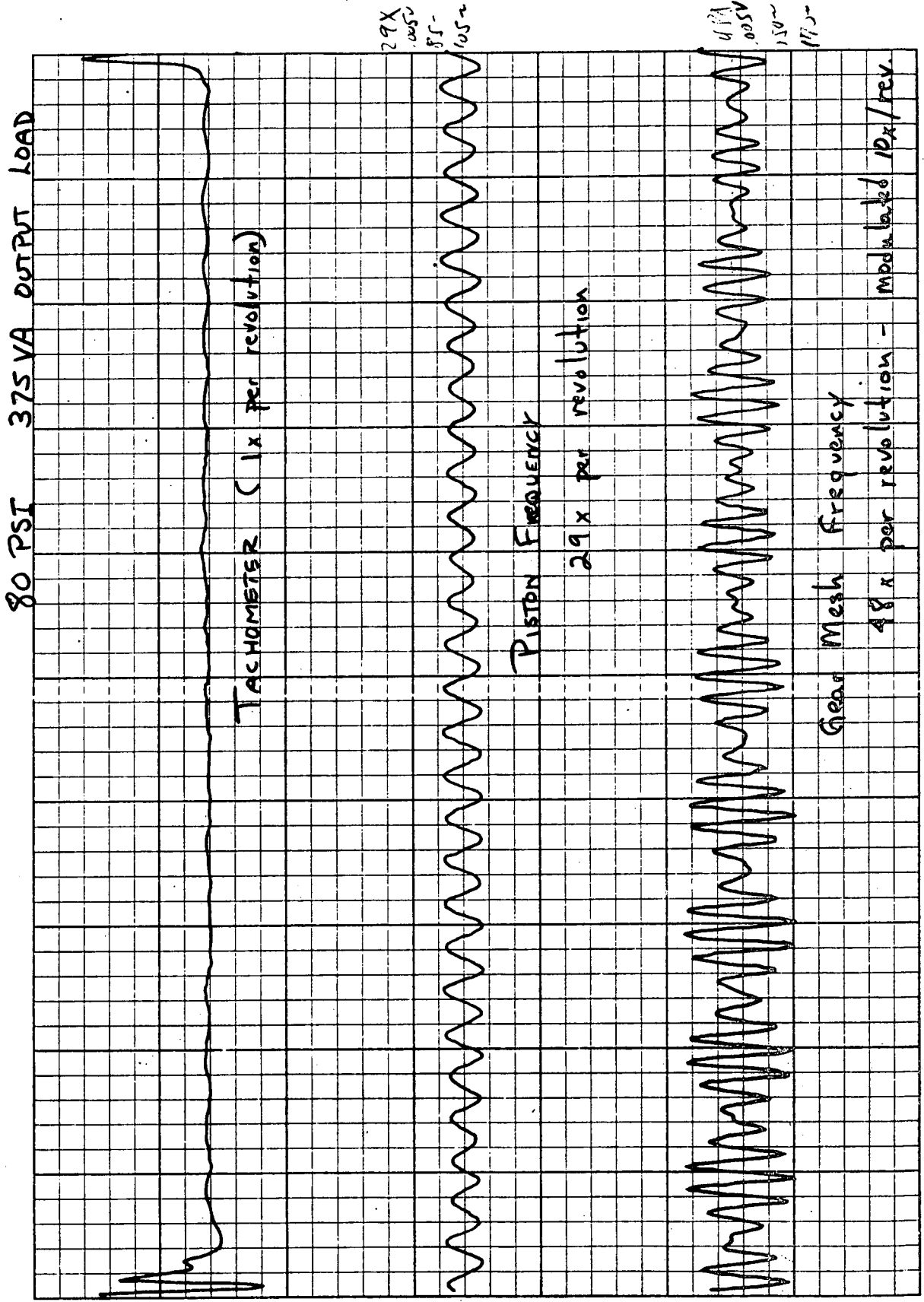
Figure 3-13

Figure 3-14

Figure 3-15

80 PSI   400VA LOAD   9B #2   2 REV

1 cycle

LEAKAGE BETWEEN ADJACENT PISTONS
(RECTIFIED)

80 PSI   375 VA LOAD

8B #2

10 ms/div

30v 8

1 CYCLE

PISTON LEAKAGE SIGNATURE

(RECTIFIED)

5 PISTONS/CYCLE
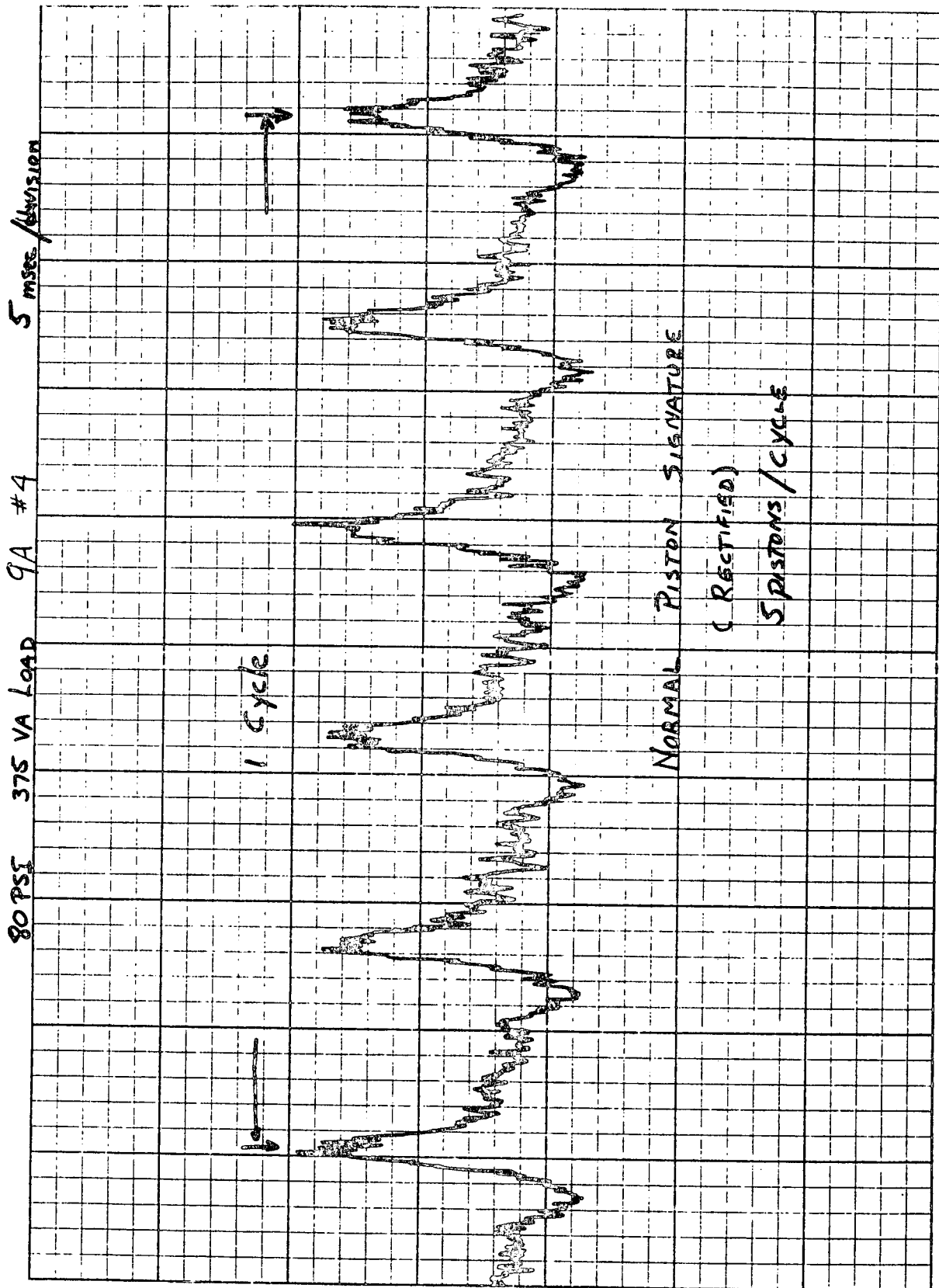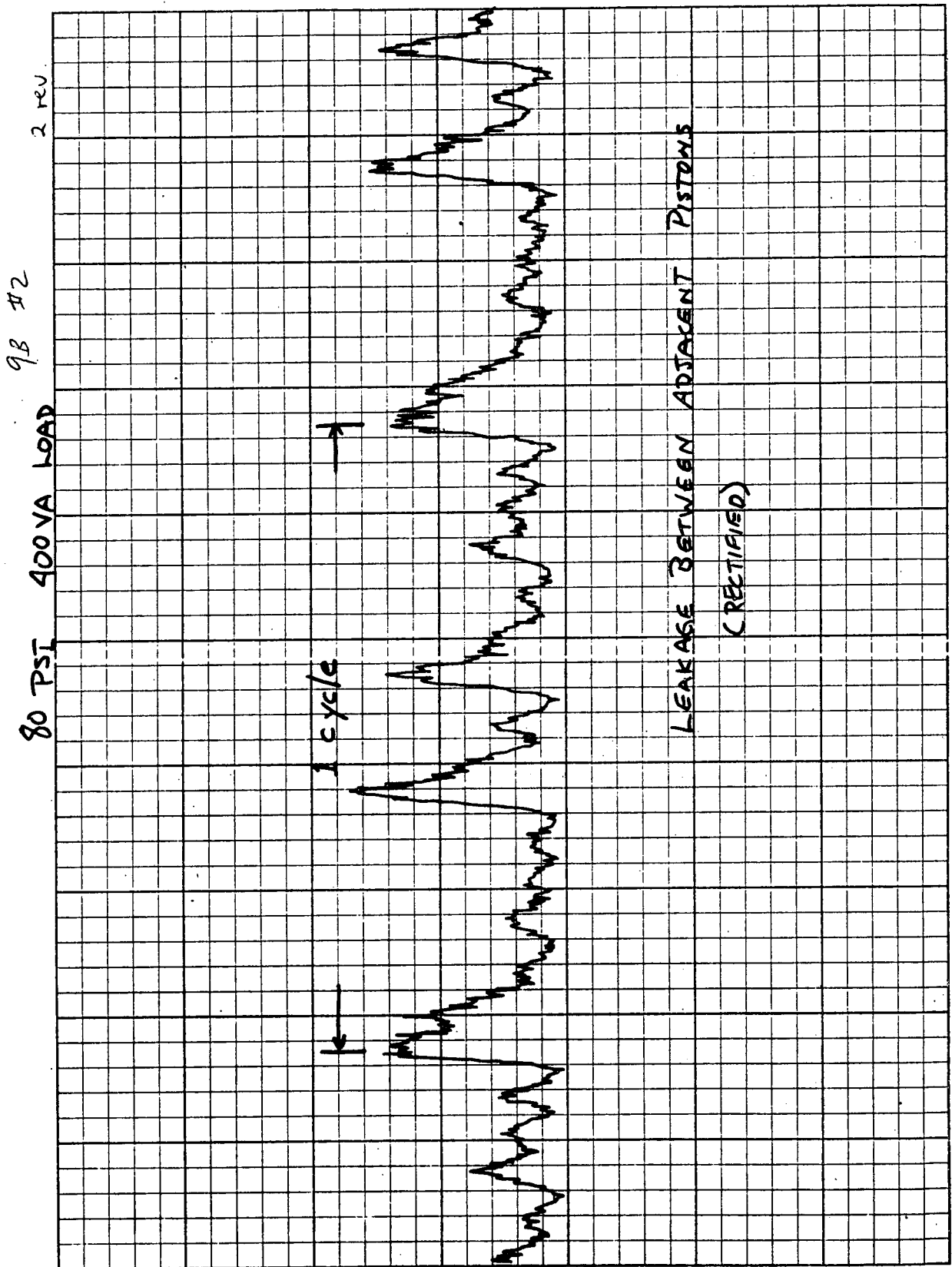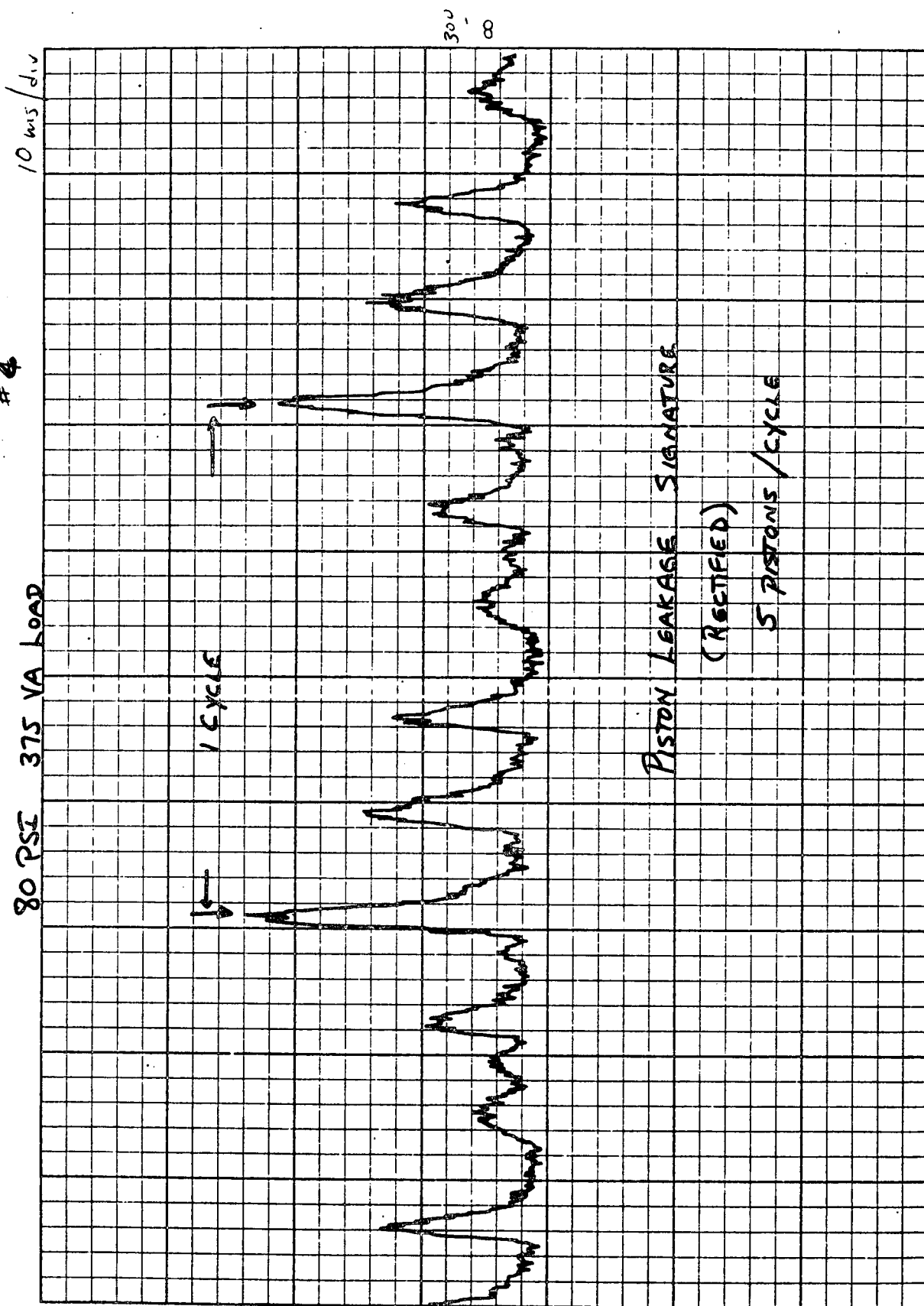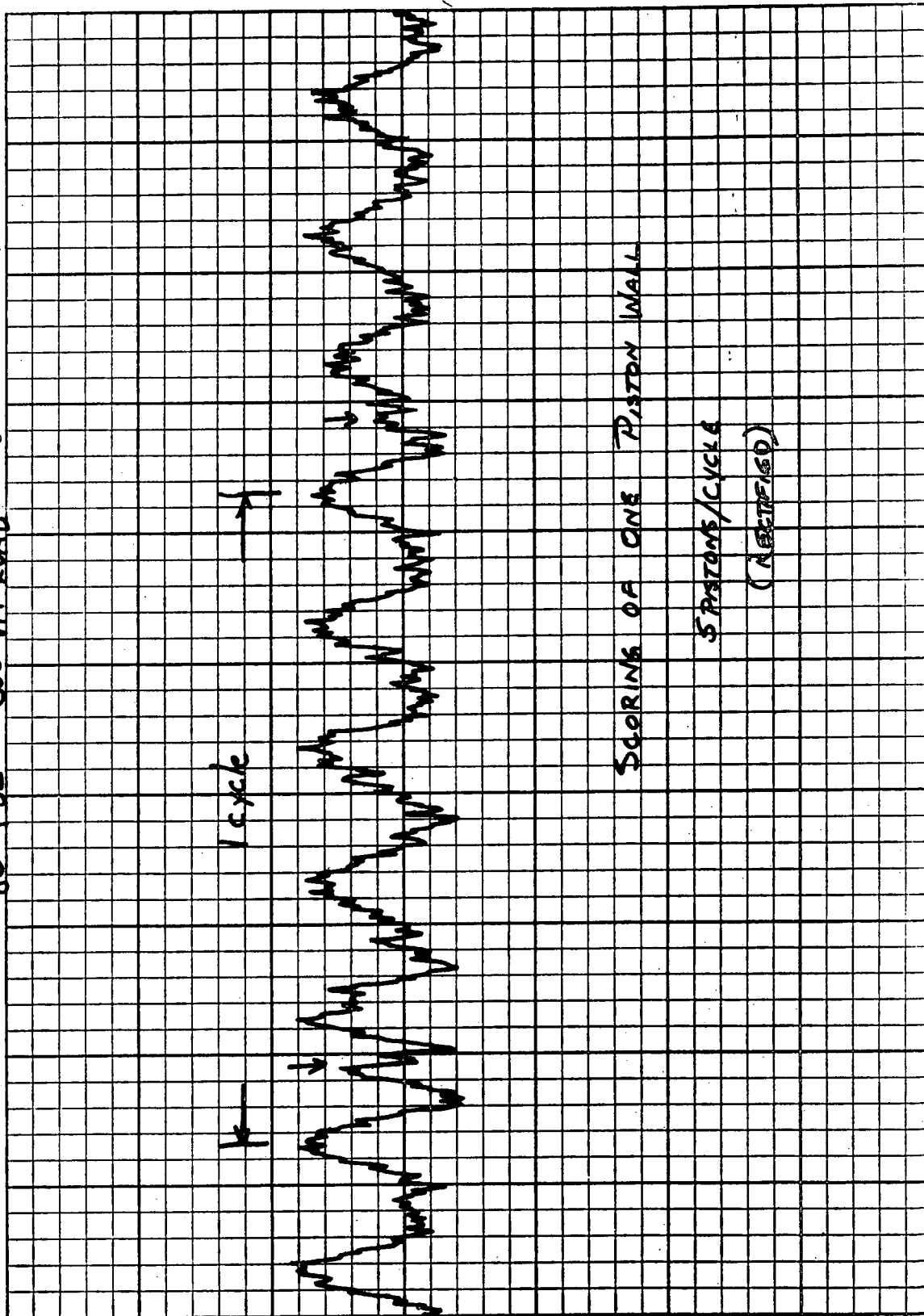
Figure 3-16

Figure 3-17

A comparison of Figure 3-18 with the normal signature of Figure 3-13 clearly identifies the presence of an inserted gear tooth defect. One tooth of the ring gear was damaged by partially grinding away the face. On the Figure, the 10x per revolution modulation introduced by the generator is still visible but now the dominating factor is the higher amplitude signal at the point of mesh of the defective gear. The last inserted defect was a small simulated spall on the outer race of the output shaft bearing. This defect was identified using the crest factor bearing monitor. Normal tests run before defect insertion gave meter readings of 20 to 30 when the data was filtered between 100 to 500 Hertz. When the defect had been inserted, the readings increased to 40. The maximum indication on the meter is 50, but a further enlarged defect caused the meter to go off scale. It was not possible to get good results with the summation analysis technique, probably because of speed instabilities or bearing ball slippage. The predicted tones and defect periodicities were previously denoted.

3.4.4 BLOWER—ROTRON HF P5803L

Testing of the blower consisted of mounting an accelerometer radially on the outer housing and counting the blades (5 per revolution) for a speed indicator. Tape recorded data was analyzed with a tracking frequency analyzer and summation analysis. Figure 3-19 shows three revolutions of averaged data. The top fan blade trace indicates the speed was 3600 rpm. The tracking analyzer output in the second trace indicates that the speed is varying slightly at twice per revolution. Correspondingly, the vibration amplitude is modulated at twice per revolution as shown in the third trace. The fundamental frequency of that vibration is 900 Hz, or twice the power frequency. The modulation also visible in trace four results from interaction between the rotor imbalance and the slip speed.

Figure 3-20 illustrates the presence of a bearing defect in one fan. The top data trace shows a repeating pattern, but more significant is the variance curve showing the repetitive impacts at the predicted period of 8 milliseconds. A second fan analyzed with the same parameters shows no such defect present (Figure 3-21). The defect in fan 960142 was not inserted, but occurred in the as-received condition. Teardown confirmed the defect was corrosion of the bearing outer race.

3.4.5 MOTOR GENERATOR SET

A 1.5-kilowatt motor generator set was tested for two controlled defects; a spalled ball bearing and a defective commutator with one bar lowered by 1 mil. An internal accelerometer mounted on the brush holder, an external accelerometer mounted on the housing, and a current probe were used to acquire data from the set. As shown in the scope traces of Figures 3-22 and 3-23, both the external and internal accelerometers detected the low commutator bar. The current probe also shows the arcing occurring for each brush crossing the low bar.

A faulty bearing in the set would have a predicted repetition period for an outer race defect of about 2 milliseconds. With the summation analyzer self-triggered on the peaks in the data, the three traces of Figure 3-24 were obtained. Each trace corresponds to a different accelerometer placement.

Figure 3-18

Figure 3-19

3-24

SWEEP TIME 5 MS/DIV   RUN 12A/

CH

Bearing Signature

Variance

CH

Filt
Freq

Figure 3-20

3-25

Figure 3-21

SWEEP TIME **5** MS/DIV

RUN *12B/*

NORMAL BEARING

VARIANCE

CH

CH

Filt

Fre
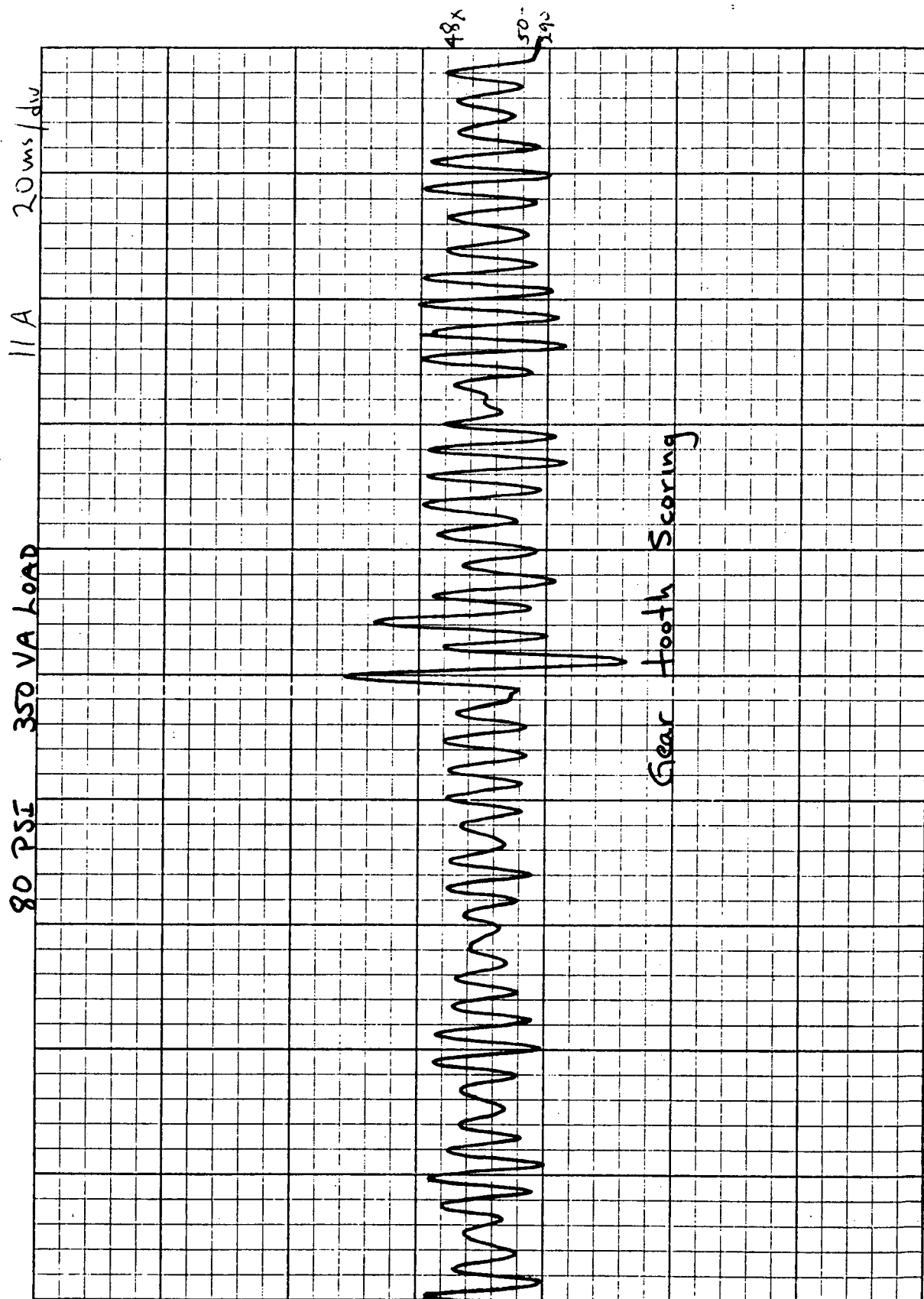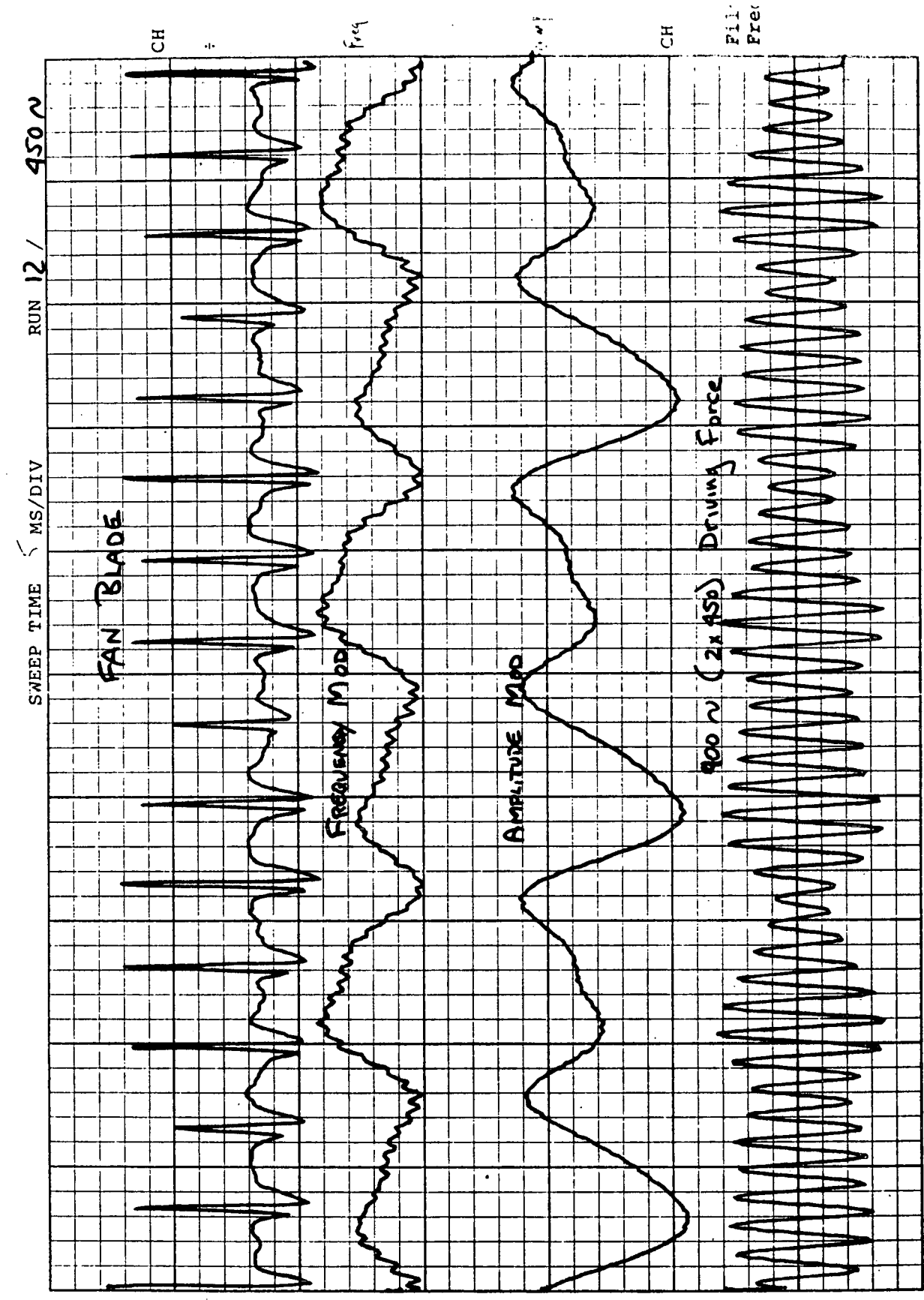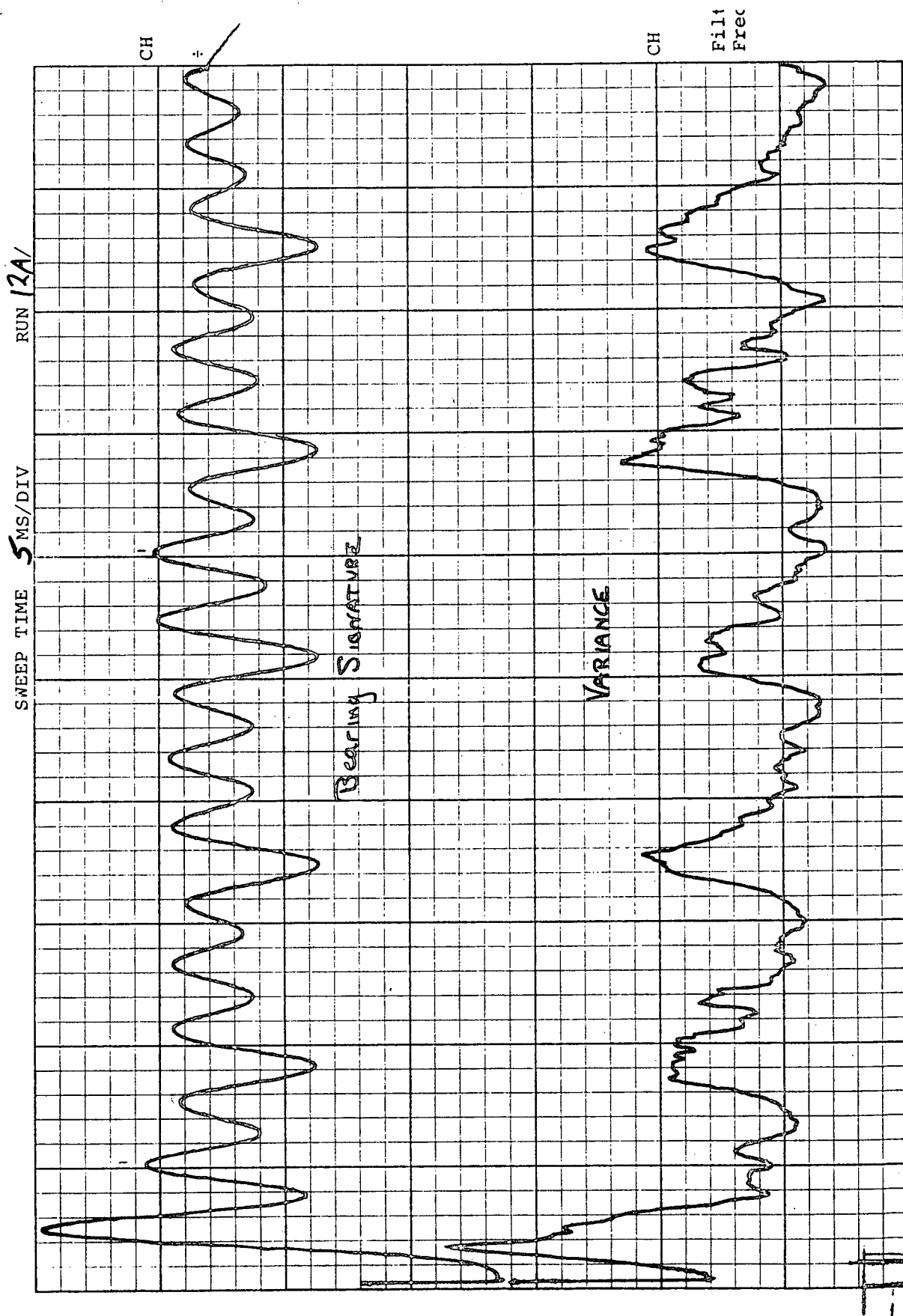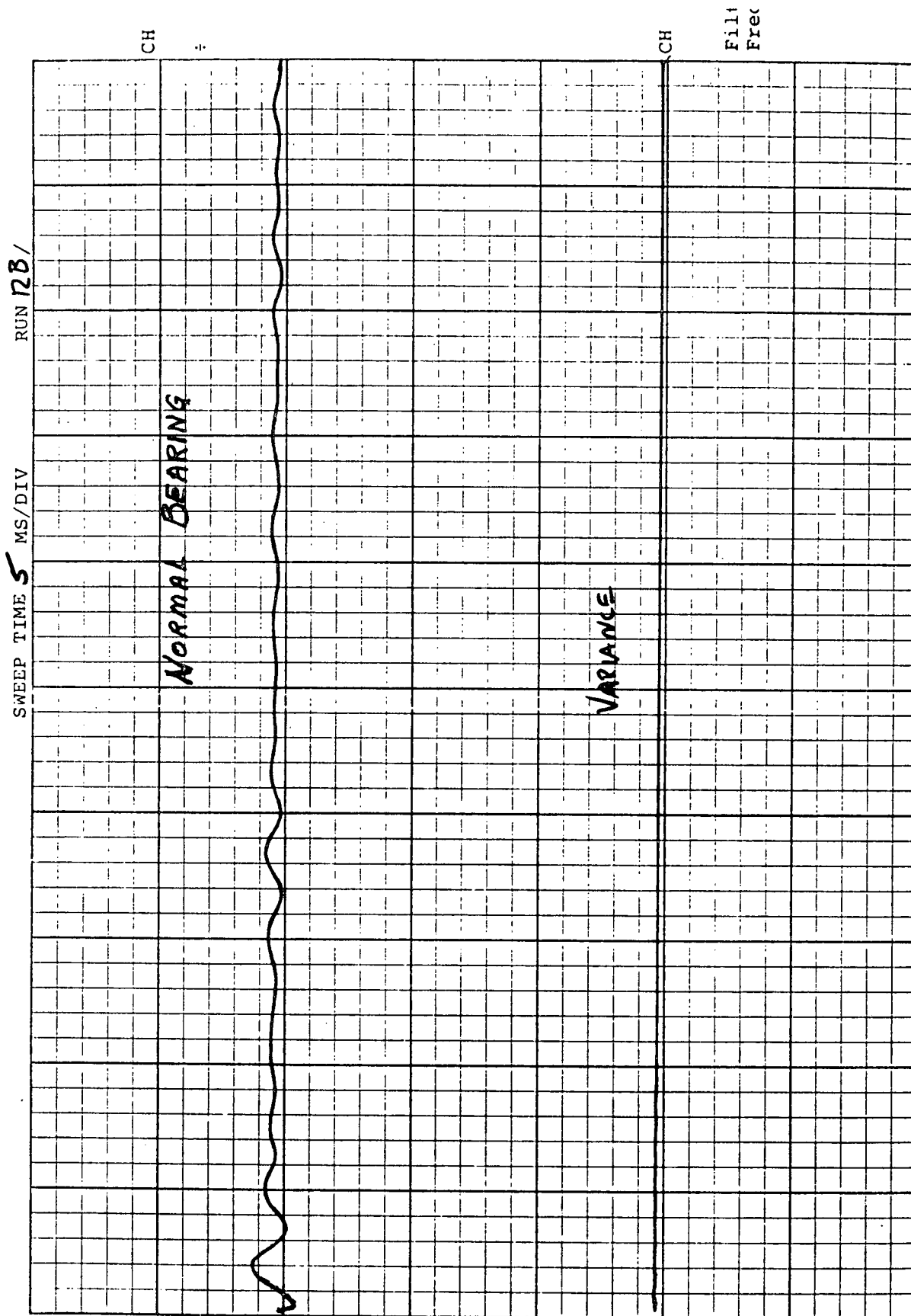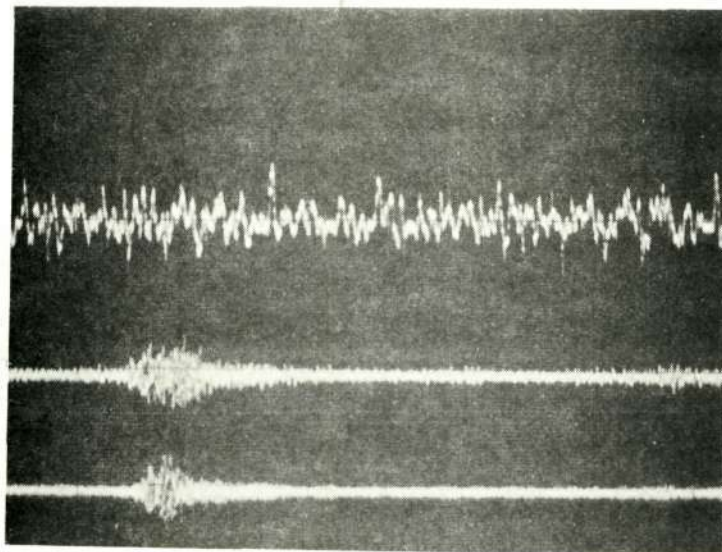
Current Probe
Output
(8 mV/cm.)

Internal Accelero-
meter
(16 g/cm.)

External Accelero-
meter
(16 g/cm.)

Figure 3-22
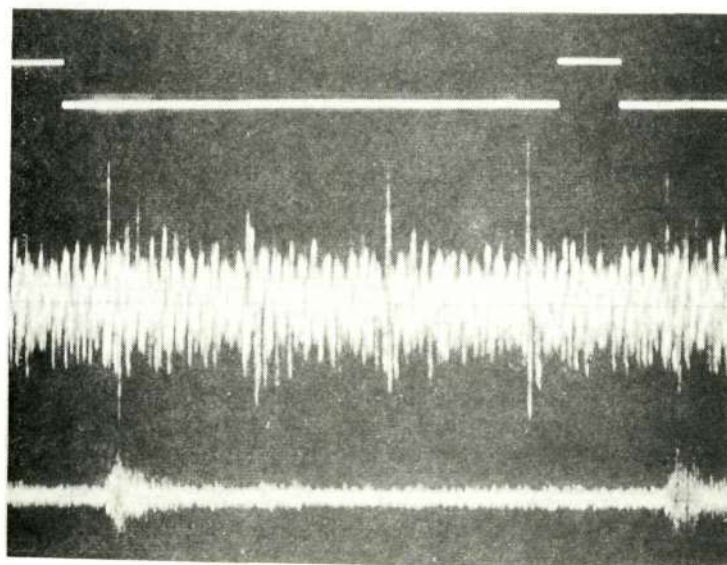
1/rev marker

Current Probe
Output
(20 mV/cm.)

Internal Accelero-
meter Output
(16 g/cm.)

Figure 3-23
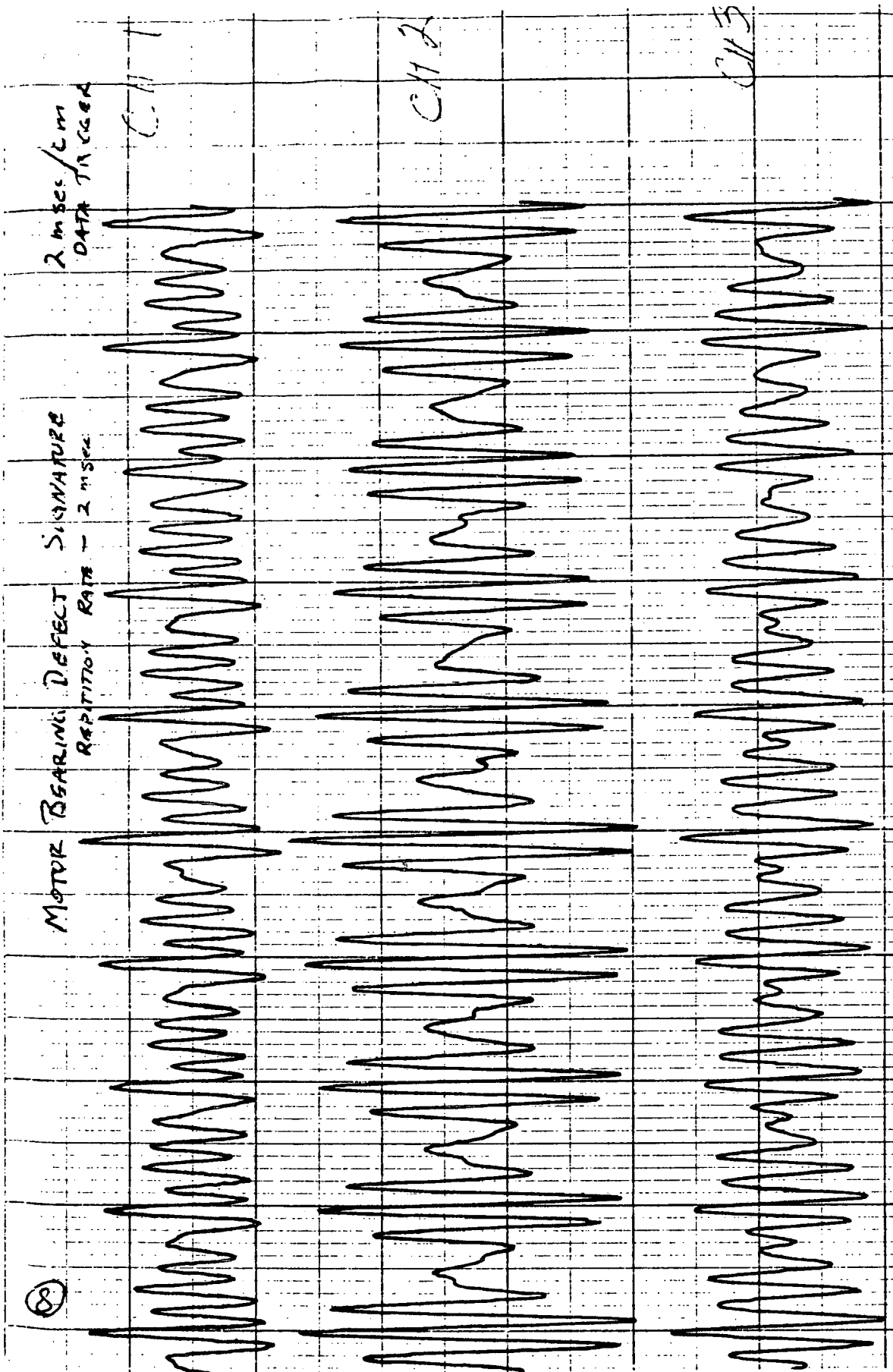
Figure 3-24

SECTION IV

STRUCTURE BORNE ACOUSTICS IMPLEMENTATION

4.1 SBA IMPLEMENTATION METHODOLOGY

As an operational non-destructive checkout technique, structure borne acoustics is in the embryonic stage. While some laboratory work has been accomplished, very limited operational implementation, and that only in the most rudimentary form, has been achieved. The work performed in this study has shown that an orderly implementation of the SBA technique involves a set pattern and sequence of events, each ingredient of the pattern having its own decision-making subroutines. This general pattern may be followed for each implementation and is shown diagrammatically in Figure 4-1. The general methodology presented can be applied to each mechanical component or system in a cookbook type approach; thereby minimizing time and cost for multiple component SBA implementation.

4.2 STRUCTURE BORNE ACOUSTIC HANDBOOK

For the purpose of bringing together, under one cover, information concerning those elements of the various technologies essential for understanding and implementing structure borne acoustics, an SBA handbook has been compiled. The handbook is attached to this report as Appendix D and is organized so that it can be removed and stand by itself as a reference document. Detailed information regarding the different aspects of SBA implementation are documented in this handbook. The contents of the handbook is shown by the outline tabulated in Table 4-1.

4.3 SYSTEM CONSIDERATIONS

4.3.1 GENERAL

This study was chartered to examine specific mechanical components using structure borne acoustic techniques and to evaluate the applicability of SBA to the three acoustic categories of mechanical devices, transient action, flow noise, and cyclic. Implementation of SBA into an operational environment must consider a systems approach to automatic readiness assessment, application to multiple devices performing interrelated functions, with automated decision (go, no-go, caution) processing.

The capability for readiness assessment of mechanical devices using SBA techniques exists today but has seen only limited operational implementation. Examples include:

a. Five hydraulic components associated with NASA-Goddard tracking antennas are acoustically monitored. Taped data is analyzed at GSFC. This is not a real-time system.

b. Real-time bearing monitors for the DC-10 aircraft engines are available as an option.
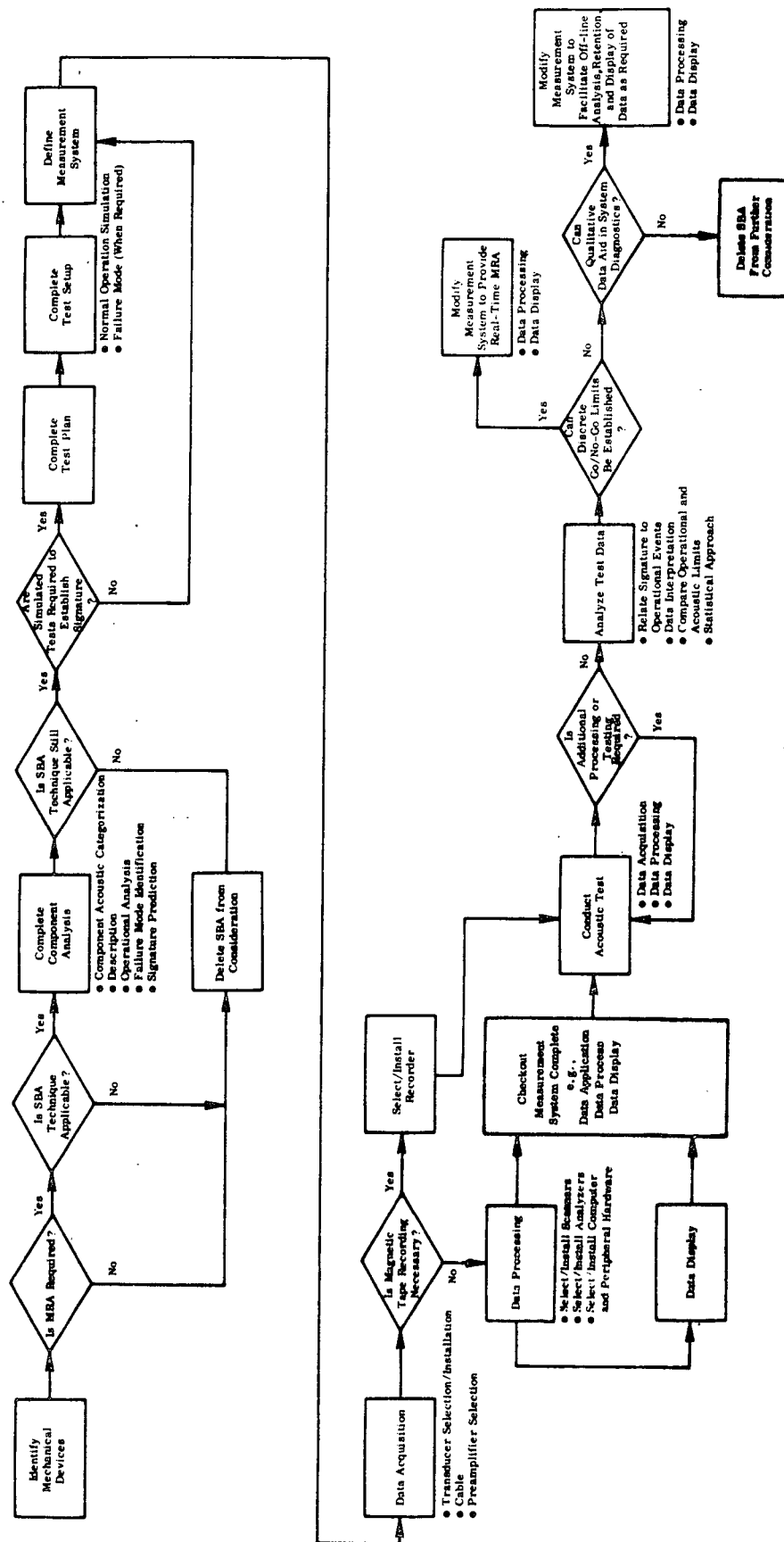
Figure 4-1. Structure Borne Acoustic Methodology

Table 4-1
SBA Handbook Outline

4-3

Real-time automatic readiness assessment on a system basis using SBA techniques can yield the greatest efficiencies through consideration of:

a. The level of processing hardware dedication.
b. SBA implementation for the more critical mechanical devices.
c. Integration with conventional existing instrumentation.

4.3.2 PROCESSING HARDWARE DEDICATION

Consider two system approaches, one typical of present techniques having the capability for limited monitor and control, the other having the additional capability for automatic self-contained readiness assessment utilizing SBA. The hardware functions required in either approach include:

a. Bidirectional communication between the mechanical device and the data bus.
b. Command decoding, data encoding (a common bus requires unique addresses for each mechanical device).
c. Electrical/mechanical command interface provides commands to the mechanical device and power for execution.
d. Transducers and associated signal conditioning to sense mechanical device physical parameters (e.g., pressure, position).
e. Processing to examine data to determine data validity, mechanical device operational readiness, and proper execution of command inputs.

The major difference between the two approaches is the processing required for automatic readiness assessment. Ideally, this processing capability should be located as near the mechanical component as the overall system concept will allow. The degree to which this additional processing should be concentrated is dependent on the following considerations:

a. System operational philosophy—need for subsystem autonomy, manual or by-pass modes of operation, control, and monitor.
b. System flexibility philosophy—need for real-time transfer of diagnostic routines or programs, changing limits, etc.
c. System data transmission—data transfer rates, verification, number of data bus interfaces, multiple data buses.
d. System monitoring philosophy—status only, status plus data call up, display∧by exception.
e. Component complexity—magnitude of processing required to provide readiness assessment.
f. Component similarities—similarities of component processing requirements (hardware and software).
g. Component density—population of components requiring readiness assessment.

Implementation of SBA on a system basis is initially expected to involve an area of high component density, e.g., portions of the crawler-transporter or on the ML. This would

lead to the expectation that SBA processing for that area would be concentrated at one location. To be consistent with the data transmission considerations, some pre-processing or filtering could be accomplished at the mechanical component to reduce transmission bandwidth requirements.

4.3.3   COMPONENT CRITICALITY

The operational integrity of a mechanical device is presently established through extensive manual checkout which includes exercising the component in conjunction with observation, by a trained "eye and ear". This contrasts significantly with the verification process for electrical/electronic hardware which can be evaluated (automatically, if desired) through the many electrical parameters such as power out, voltage, current, resistance, pulse shape, and timing. As a result of mechanical device criticality, frequent use of redundancy is required. This improves the probability of successfully completing a mission, at the expense of increased complexity, periodic maintenance, and manual verification.

An advanced space program comparable to the Saturn V program in size and complexity will require over thousands of mechanical components in the flight hardware and associated ground support equipment. The impracticality of instrumenting all mechanical components is hardly contestable based on cost, reliability, and consequence of failure considerations.

Initial reliability efforts should be directed toward the identification of relative criticality for each component. Considerations employed in a criticality analysis of this sort include:

    a.   Potential failure effect for each failure mode.
    b.   Probability of the most severe failure effect actually occurring.
    c.   Probability of failure in a particular mode.
    d.   Time period in which the failure takes place.
    e.   Failure rate of the mechanical device.
    f.   Environment of the mechanical device.

The assignment of relative numerical weights to each of the above provides a quantitative basis for comparing the criticality of a number of components, thus providing a rationale for selecting components for SBA implementation and the more critical failure modes which must be detected.

4.3.4   USE OF CONVENTIONAL/EXISTING INSTRUMENTATION

SBA instrumentation must be integrated by the processing hardware with existing or conventional instrumentation to obtain maximum readiness assessment capability. This reasoning is based on the rationale that:

    a.   SBA cannot provide all the data necessary for readiness assessment decisions.

b. Where either existing instrumentation or add-on SBA can provide required readiness assessment data, the use of or change to SBA would be difficult to justify.

c. Conventional instrumentation must provide a frame of reference to the decision logic. Using an air motor mounted acoustic accelerometer as an example, the accelerometer should have no output unless supply air has been commanded on and is present at the air motor inlet. Status of the supply air would be detected by conventional instrumentation and be provided to the readiness assessment decision logic.

4.3.5 SUMMARY

Implementation of real-time SBA techniques, integrated on a systems basis can provide many maintenance and operations efficiencies including:

a. Maintenance when required versus a set time between overhaul based on the capability of SBA to detect incipient malfunctions.

b. Early detection of failure or degradation, thereby reducing repair costs.

c. Reduction of GSE and flight hardware verification time.

d. Examination of hardware performance data on an exception basis as opposed to a lengthy review of all data to determine component condition.

4.4 RECOMMENDED IMPLEMENTATION PROGRAM

To implement the structure borne acoustic test technique efficiently into future space programs will require an orderly approach. The recommendations presented here take into account past and existing shuttle related studies in terms of their influence upon structure borne acoustics.

The hardware utilized for the implementation of SBA was considered from the standpoint of what further technique developments would enhance SBA, as well as, what equipment group needs emphasis. The significant equipment groups are the mechanical components, transducers and signal processing equipment.

The recommended developmental programs represent the activity necessary for the accomplishment of mechanical component readiness assessment by SBA while reflecting 1972/1973 technology. The recommended programs permit an incremental funding approach which will provide information decision points, as to the most effective means for applying the SBA techniques to advanced space programs.

4.4.1 MECHANICAL COMPONENT DEVELOPMENT

Advantages of the SBA techniques cannot be fully exploited until more is known about individual mechanical device functional parameter limits, i.e., what are go, no-go, and caution mechanical discriminants and quantitative boundaries. A testing program is recommended which will establish these discriminants for selected advanced space program mechanical components. Estimated cost of this program is $150,000 and the recommended schedule duration is 12 months.

Identification of mechanical devices requiring readiness assessment by SBA must be established. This task includes development of ground rules and selection rationale and generation of a listing of line replaceable units (LRU's) for each space program requiring mechanical readiness assessment by SBA. Estimated cost is $50,000 and the recommended schedule duration is 6 months. Both of the above tasks can be integrated into the early design phases of a specific space program.

4.4.2 TRANSDUCER DEVELOPMENT

Transducer technology, as it exists today, is adequate for SBA implemented in near-future space programs; however, the implementation of extensive "add on" SBA accelerometers may require the adjustment, variation, or improvement of certain selected transducer parameters such as range sensitivity or resolution. It is felt the magnitude of these changes is within the scope of existing transducer design capability; therefore, no study or development is needed to support structure borne acoustics. The area of greatest concern is in sensitivity requirements of transducers to detect low-level leak noises. A parallel study in this area is being sponsored by KSC. Hence, this aspect was not researched in detail.

4.4.3 SIGNAL PROCESSING EQUIPMENT

Like transducer technology, the signal processing equipment, as it exists today, is adequate for SBA implementation. There are numerous processing equipment design trade-offs that can only be efficiently completed subsequent to the definition of mechanical components to be assessed by SBA. The most significant of these trade-off areas include:

a. Level of processing dedication or distribution—individual component logic devices or higher-order processors for multiple components.
b. Degree of processing equipment modularity.
c. Memory and software considerations.
d. Self-test requirements.
e. Packaging techniques, physical size and power consumption.
f. Function allocation—hardware, software, or firmware.
g. Signal conditioning techniques—dedicated or time shared.
h. Processing—amount of analog preprocessing or digital processing.

4.4.4 SBA SYSTEM IMPLEMENTATION

As noted above, there are no equipment studies or development programs that are mandatory prior to design implementation of the SBA technique. Implementation of the SBA technique can be achieved with today's transducer and processing equipment technology; tomorrow's equipment advancements will serve to enhance the concept.

The key problem of implementing this technique lies not with individual equipment development, but rather in making all of the elements of an SBA system work together. This study has shown that structure borne acoustics test technique has applicability to the real-time readiness assessment of mechanical devices. The necessity of baseline

testing for each component, however, coupled with the sophistication of equipment, inherent system variables, and the experience which must be developed to properly use the equipment and to interpret the acoustic signature discriminants all work in combination to dictate proceeding with caution for any near-term, wide-scale operational implementation.

It is recommended that no further expenditures of time and energy be made at this time to study the feasibility or advisability of utilizing this technique in a generic sense. It is further recommended that a prototype operational system be implemented on an on-going program such as the Skylab on a "piggy back" basis. This prototype operational system would be applied to real-time readiness assessment and performance monitoring of a limited number of cyclic and transient components (approximately 15). Cost would be approximately $260,000 and the program could be implemented within an estimated 10 to 12 month time frame.

The implementation and use of this prototype SBA system will provide the operational and design experience in component baseline testing, use of equipment, and interpretation of acoustic signature discriminants. Additionally, it will provide a data baseline from which a meaningful decision can be made for broader implementation of the SBA technique on future space programs.

4.5 COST OF IMPLEMENTATION

Estimation of SBA implementation cost requires a number of assumptions. Among the more basic costing assumptions are the following.

- Accomplishment of recommended implementation plan.
- Incorporation of the data bus communication philosophy.
- Implementation of the mechanical device SBA readiness assessment concept will be initially accomplished through rework of existing mechanical devices, i.e., add on transducers.
- The advanced space program considered will be equivalent in ground and flight hardware requirements to the Saturn V program.
- A significant amount of instrumentation and processing hardware will be required for an advanced space program, regardless of the extent to which the readiness assessment philosophy is implemented.

The estimated cost for initial implementation of SBA mechanical readiness assessment capability is contained in Table 4-2. The summary does not include the sustaining costs, nor do the costs reflect the considerable return on investment that could be realized with the implementation of SBA readiness assessment and fault isolation. Portions of the developmental programs could be integrated into, and costed with the actual design phase. For convenience purposes, however, the cost estimates for these activities are segregated. Detailed assumptions that were used in arriving at these cost estimates are presented in Appendix C.

Table 4-2

Summary of SBA Implementation Costs

	Total Cost ($)
Development Programs	460K
Design	1,290K
Manufacturing	3,394K
Testing	1,830K
Programming	120K
Less Cost of Other Instrumentation (25 percent)	(1,774K)
Cost of Implementing SBA Mechanical Readiness Assessment	5,320K

As noted in the foregoing table, a significant proportion of the enumerated expenses (estimated 25 percent) will be required regardless of the measurement, display, and checkout hardware selected as an alternate to the SBA readiness assessment concept. Potentially, there are system areas where significant cost savings would accrue with the implementation of the SBA philosophy, though these are difficult to identify quantitatively. Some of the considerations which would reduce the cost differential between implementing and not implementing SBA include:

- Maintenance when required versus a set time between overhaul based on a failure prediction capability.
- Early detection of incipient failures, thus reducing repair costs.
- Implementation of SBA would reduce the dollar and time costs required to verify hardware ready to support an operational exercise.
- Automatic readiness assessment will reduce data reduction and fault identification time based on evaluation by exception as opposed to a lengthy review of all data to determine component health.
- The sustaining cost of a complex having automatic self-contained readiness assessment at the component level will be less for maintenance and operation.

There are strong and valid arguments for each of the above examples. It must also be recognized that there are some negative cost factors to consider. For example:

- Personnel will require retraining in a new philosophy.
- Implementation will require a significant increase in the amount of instrumentation and processing/communication hardware requiring maintenance and calibration.

SECTION V

SUMMARY

5.1 GENERAL

Those conclusions and recommendations resulting from this study effort are summarized herein.

5.2 CONCLUSIONS

1. Acoustic signature limits can be established for specific component failure mode limits; however, much work must be done to define the mechanical device failure mode limit itself, e.g., how much leakage is no-go? This task was outside the scope of this acoustic test program.

2. The structure borne acoustic test technique has greatest applicability to cyclic mechanical devices. It also has applicability to transient acoustic generators, but has little immediate practical application to mechanical devices that are only "flow noise" generators.

3. Each mechanical component must have its normal-operation acoustic signature emperically established.

4. The existing state-of-the-art accelerometers and signal processing equipment is adequate for the implementation of the SBA technique.

5. The SBA test technique has significant potential for achieving real-time readiness assessment of mechanical devices. The necessity of component baseline testing, inherent system variables, and the experience which must be developed to properly use the equipment and to interpret the acoustic signatures dictate proceeding with caution for any near-term wide-scale operational implementation.

6. The cost of full-scale implementation of the SBA technique on a future space program equivalent in size to the Saturn program is approximately 5 million dollars. The cost estimates broken down into broad categories are:

   a. Development—$460K
   b. Design—$1,290K
   c. Manufacturing—$3,394K
   d. Test—$1,830K
   e. Programming—$120K
   f. Less Cost of Conventional Instrumentation—$1,774K

<u>RECOMMENDATIONS</u>

Those programs which are recommended for implementing SBA are:

1. Develop basic significant physical parameters of mechanical components. Estimated cost is $150,000 and estimated schedule duration is 12 months.

2. Develop selection rationale and list of mechanical devices that will utilize the SBA technique for readiness assessment. Estimated cost is $50,000 and estimated schedule duration is 6 months.

3. Implement a prototype "piggyback" SBA system on the Skylab Program for selected mechanical components. The estimated cost of implementing this prototype system is $260,000.

4. The SBA test technique has too much potential to be ignored by users of large quantities of mechanical devices. There are applications at Kennedy Space Center, other than real-time mechanical readiness assessment, where the structure borne acoustic technique may be useful. Examples are component bench test facilities and support operations analytical laboratories. It is recommended that these possibilities be fully explored.

APPENDIX A

SCHEDULED TASK PERFORMANCE

Scheduled Tasks	Completion Dates
Task I:	
Assemble Acoustic Data and Component Documentation	November 24, 1971
Select Representative Components	November 24, 1971
Derive Analytical Description of Acoustical Signature	December 31, 1971
● Transient Action Component	December 1
● Flow Control Component	December 6
● Cyclic Action Component	December 31
Develop Test Plan	December 31, 1971
● Transient Action	December 15
● Flow Control	December 23
● Cyclic Action	December 31
Task II:	
Transient Action Component	February 23, 1972
● Test Set-Up	January 6
● Conduct Operational Test	February 4
● Verify Analytical Description	January 28
● Establish Measurement Techniques	January 28
● Determine Assessment Limits	February 2
● Failure Mode Test	February 29
● Failure Mode Measurement Techniques and Assessment Limit	February 23
Flow Control Component	March 28, 1972
● Test Set-Up	January 24
● Conduct Operational Test	March 7
● Verify Analytical Description	March 10
● Establish Measurement Techniques	March 10
● Determine Assessment Limits	March 17
● Failure Mode Test	March 17
● Failure Mode Measurement Techniques and Assessment Limits	March 28

Scheduled Tasks	Completion Dates
Cyclic Action Component	April 21, 1972
● Test Set-Up	February 24
● Conduct Operational Test	March 17
● Verify Analytical Description	March 24
● Establish Measurement Techniques	March 26
● Determine Assessment Limits	March 30
● Failure Mode Test	April 19
● Failure Mode Measurement Techniques and Assessment Limit	April 21
Outline Structure Borne Acoustic General Methodology Handbook	February 21, 1972
Select Task III Test Components	March 3
Task III:	
Complete Analysis of Task II Test Data	May 4, 1972
Complete Structure Borne Acoustics Handbook	April 28, 1972
Verify Validity of General Methodology	
● Test Component No. 4	May 1, 1972
● Test Component No. 5	May 5, 1972
Develop Summary Recommendations	May 5, 1972

APPENDIX B

MECHANICAL COMPONENT TEST DATA

This Appendix contains a component description, test schematics/drawings, and typical test data, raw and tabulated, for the five representative components which were tested:

B1   –   Solenoid Valve 75M08825-3

B2   –   Regulator 75M08831-1

B3   –   Air Motor 70A66

B4   –   Blower HF-PS8032, Series 355KS

B5   –   Motor Generator-Motor-5K225D38, Generator-1.5 kw

APPENDIX B1

SOLENOID VALVE (75M08825-3)

The 75M08825-3 solenoid valve is a three-way, two-position, normally open, magnetically operated valve with a built-in electrical position indicator switch. The valve contains a coil and core assembly, a position indicating switch, stem, cage, and sleeve. When the solenoid is deenergized the CYL-1 port and the NO port are common. When the solenoid is energized, the stem is actuated and CYL-1 port is common with the NC port. The flow is bidirectional, and the valve can be mounted in any position and is qualified for use with GN_2. (See Figures B1-1 and B1-2.)

General information about the solenoid valve is as follows:

Operating Pressure	3000 psi
Proof Pressure	4500 psi
Operating Temperature	0°F to +165°F
Pressure Drop	Equivalent sharp edge orifice diameter 0.11
Operating Voltage	24 ±6 vdc
Coil Resistance	21.5 to 24 ohms at +20° C (68°F)
Rated Current	1.12 amp at 24 vdc
Ports	Per MC240-4
Fittings	Per MC237C4
Leakage	Bubble tight, internal and external
Operating Time	50 ms (not critical)
Duty	Continuous

B1-1

Figure B1-1. Cross Section View Of Solenoid Valve 75M08825-3

Figure B1-2. Solenoid Valve (Sheet 1 of 2)

INDEX NO.	NOMENCLATURE	PART NO.	VENDOR CODE	QTY
1	Lockwire	MS20995C20		AR
2	Fitting	J53S6C10	99657	3
3	O-Ring	J201J4	99657	3
4	Screw	J67A12	99657	1
5	Slug	111112-461	99657	1
6	Screw, Adjusting	144621	99657	1
7	Spring	168152	99657	1
8	Nut	116762	99657	1
9	Screw	102961	99657	2
10	Cover	102531-2	99657	1
11	O-Ring	J200A28	99657	1
12	Screw	AN500AD2-10		1
13	Nut	79LH1660-26	72962	1
14	Washer	107331	99657	1
15	Nut	107281	99657	1
16	Lock Washer	107261	99657	1
17	Armature Assembly	221071	99657	1
18	Screw	J66A4	99657	4
19	Washer	107241	99657	4
20	Receptacle	CF3102R14S-5P	77820	1
21	O-Ring	J200A17	99657	2
22	Spacer	168212-1	99657	1
23	Insulator	107311	99657	1
24	Screw	111071	99657	2
25	O-Ring	J200A2	99657	2
26	Coil and Core Assembly	222362-1125	99657	1
27	Plunger	150111-1	99657	1
28	Switch Assembly	228052	99657	1
29	Retainer	154471	99657	1
30	Stem	142602-1-1-1	99657	1
31	O-Ring	J200A7	99657	3
32	Sleeve	102831	99657	1
33	O-Ring	J200A12	99657	3
34	Seat	201892	99657	2
35	Cage	124522-3-1	99657	1
36	Body	152704	99657	1

Figure B1-2. Solenoid Valve (Sheet 2 of 2)
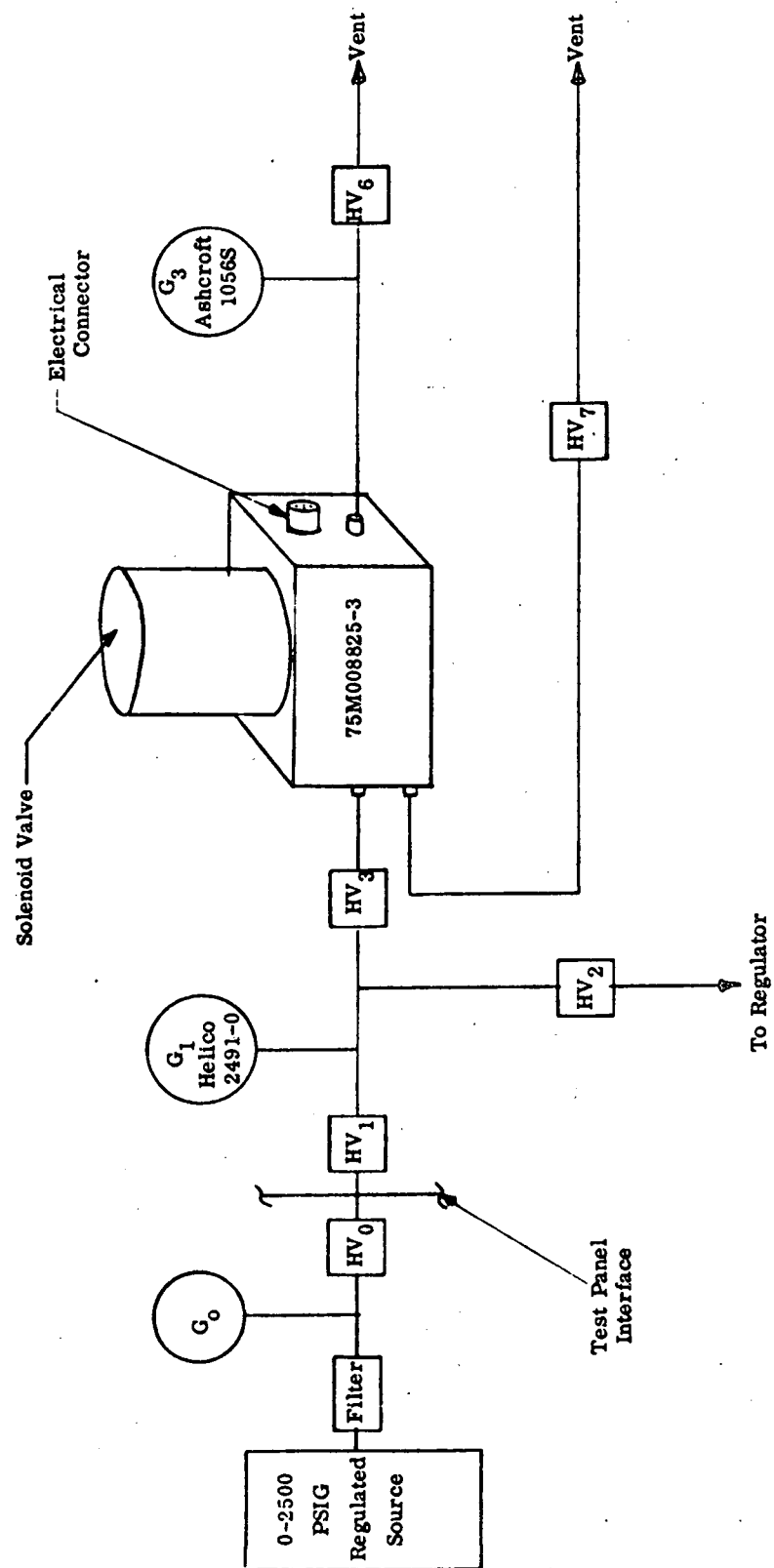
Figure B1-3. Solenoid Valve Test Mechanical Schematic

Figure B1-4. Mechanical Readiness Test Set Up Solenoid
Valve 75M08825-3 Electrical Connections

SOLENOID VALVE HISTOGRAMS

The following histograms display solenoid operating time (actuation and deactuation) by valve serial number for both normal and failure mode operations. "Turn on" and "Turn off" refer to the application or removal of voltage to the valve coil. Each vertical division is one operation, and the horizontal divisions are in milliseconds as indicated.

The data shows the repeatability of operating time and the influence of various inserted defects upon the operating times.

TURN ON   "≈"⁶ TURN OFF

SPRING COMPRESSED 1/4 TURN
Ø PRESSURE
S/N 444

SPRING COMPRESSED 1/4 TURN
1000 PSI, FLOW
S/N 444

SPRING COMPRESSED 1/2 TURN
Ø PRESSURE
S/N 444

SPRING COMPRESSED 1/2 TURN
1000 PSI, FLOW
S/N 444

Ø PRESSURE
18 VOLT INPUT
S/N 444

Ø PRESSURE
18 VOLT INPUT
S/N 906   ■ ONE OPERATION

Ø PRESSURE
15 VOLT INPUT
S/N 906

73 74 75 76   125 127 129   25 4. 5. 6. 7 8. 9 10 11 12 13 14 15 16 17

B1-8

TURN ON
Ø PRESSURE
NO DEFECT

TURN OFF

TURN ON
100Ø PSI, 3CFM FLOW
NO DEFECT

TURN OFF

■ ONE OPERATION

S/N 444

S/N 906

S/N 202

S/N 210

MS

APPENDIX B2

PRESSURE REGULATOR (75M08831-1)

The 75M08831-1 pressure regulator is a three-way spring referenced, preset pressure regulator. The pressure setting is governed by the spring cartridge assembly. The force exerted on the piston by the spring cartridge assembly forces the poppet to an open position. The poppet is held open until the outlet pressure, acting on the piston, exerts a force sufficient to overcome the spring cartridge and close the poppet. Further increase in outlet pressure will vent the excess outlet pressure down to the set pressure level. The regulator is qualified for use with GN_2.

General information about the regulator is as follows:

Inlet Pressure	4500 psi maximum
Outlet Pressure	50 to 190 psi
Proof Pressure	6750 psi
Burst Pressure	11,250 psi
Operating Temperature	0° F to +165° F
Ports	Inlet: per MC240-6
	Outlet: per MC240-8
Capacity	Flow factor
	F = 0.5 scfm/psia
Weight	2.1 lb
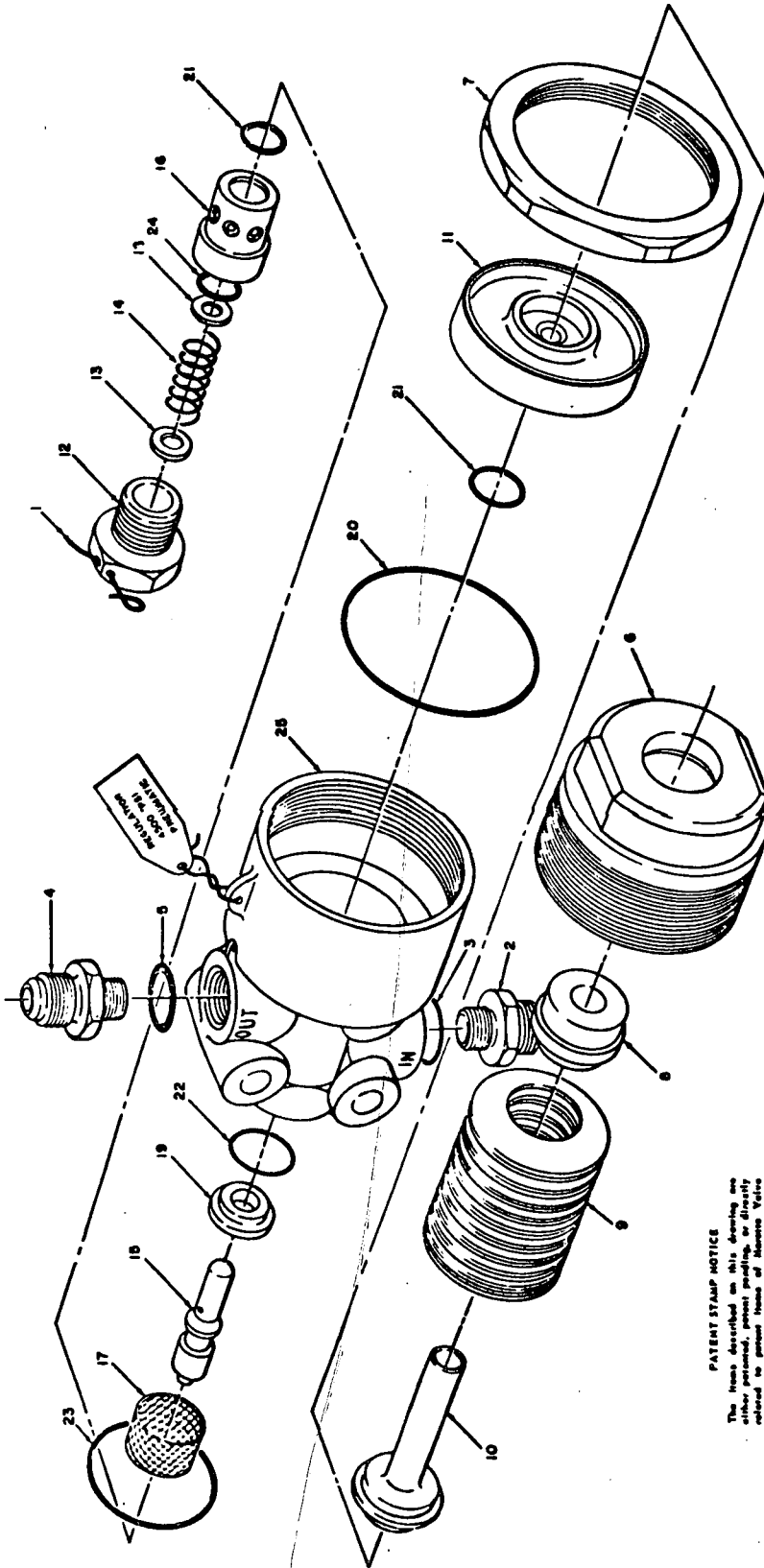
Figure B2-1. Pressure Regulator (Sheet 1 of 2)

PATENT STAMP NOTICE

The items described in this drawing are either patented, patent pending, or directly related to patent items of Monroe Valve Corporation.

INDEX NO.	NOMENCLATURE	PART NO.	VENDOR CODE	QTY
1	Lockwire	MS20995C20		AR
2	Adapter, Inlet	MC235C19		1
3	O-Ring, Inlet Adapter	MS28778-6		1
4	Adapter, Outlet	MC235C20		1
5	O-Ring, Outlet Adapter	MS28778-8		1
6	Nut, Adjusting	146392	99657	1
7	Locknut	146382	99657	1
8	Guide, Spring	146691	99657	1
9	Spring Cartridge	J205A86-22A	99657	1
10	Tube, Guide	160002	99657	1
11	Piston	160073-A1	99657	1
12	Nut, End	146342	99657	1
13	Washer	120002-104	99657	1
14	Spring, Poppet	144331	99657	1
15	Poppet	160052-3	99657	1
16	Retainer	146712	99657	1
17	Screen	147741	99657	1
18	Washer	120002-103	99657	1
19	Seat	154663-11	99657	1
20	O-Ring, Piston	J200AF136	99657	1
21	O-Ring, Poppet/Piston	J200AF12	99657	2
22	O-Ring, Seat	J200AF15	99657	1
23	O-Ring, Retainer	J200AF116	99657	1
24	O-Ring, Retainer Seat	J200AF14	99657	1
25	Body	176134-A1	99657	1

Figure B2-2. Pressure Regulator (Sheet 2 of 2)

C
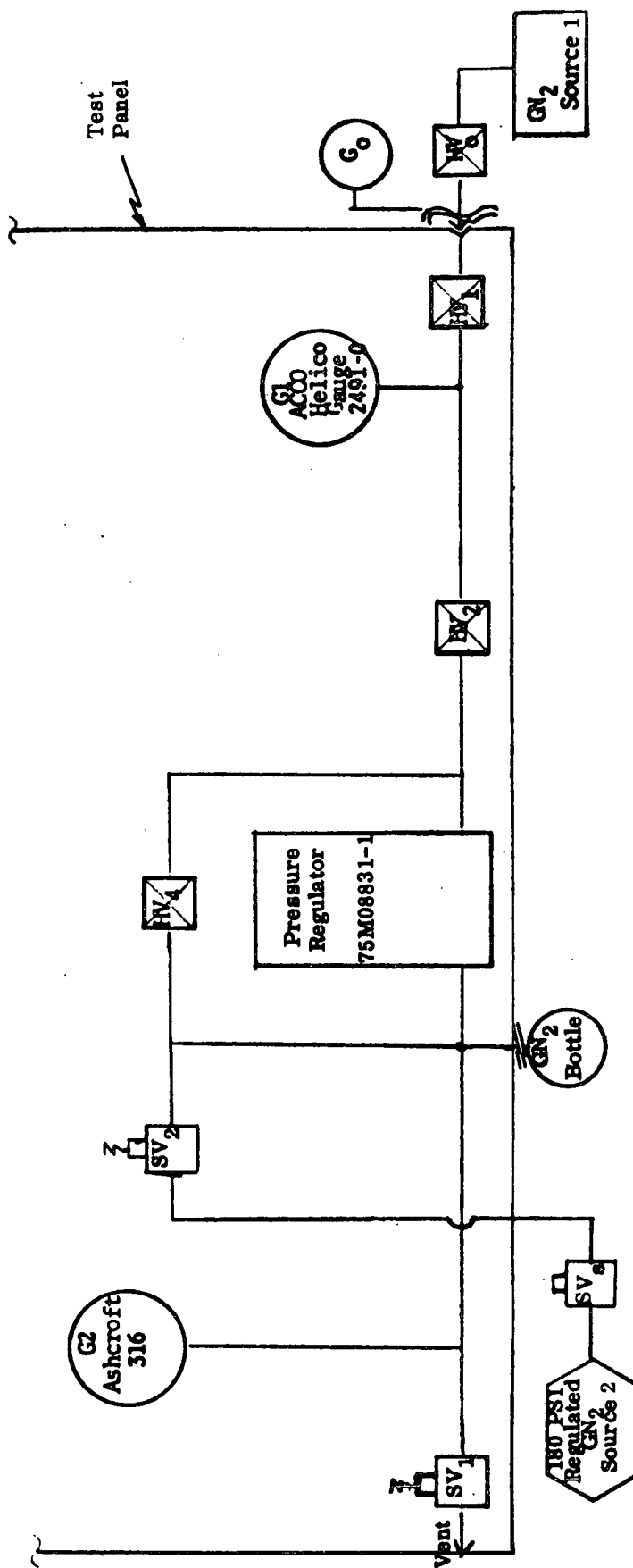
Figure B2-3. KSC Mechanical Readiness Test Panel Mechanical Connections
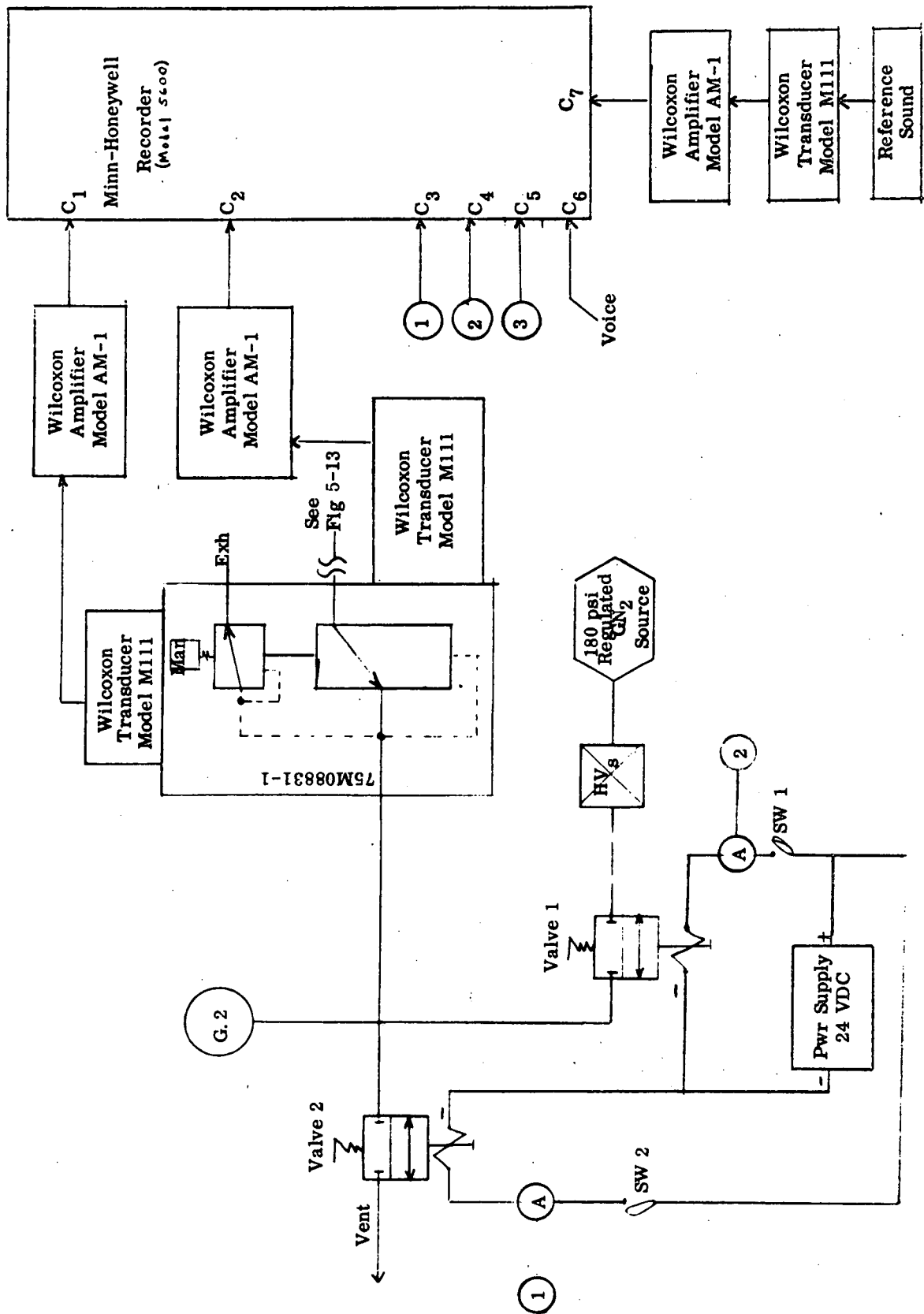
Figure B2-4. Regulator 75M08831-1 Mechanical Readiness Test Set Up, Electrical Connections

ACOUSTIC ACCELEROMETER

PRESSURE XDUCER

NOMINAL REC. 0:17:17 - 200 PSI

5 SEC

20 PSI

STABLE (NO FLOW)

EASY PRESSURE APPLIED

DECREASED

.33 P/min

PSI

B2-7

BACK PRESSURE OFF

200 PSI

DEMAND OFF

ACOUSTIC ACCELEROMETER
(ELECTRIC)

PRESSURE XDUCER

B2-8

40 PSI

B2-12

73 #2

10ms/div

300
ω
rectful

#3
2-10
100 psi 3 cfm

#1, .5V

#2, .5V

5 ns/div

B2-15

B2-17

Accel #1, .1V

Accel #2, .1V

5 ns/Div @ ??

#2
1.27

B2-20

#2
New Solenoid 1.27
#906

Normal
No Press
.2uv

Actual 4 .1V

Accel 9.32
.1V

10 ms/Divcallis

B2-21

5 ms/cm @ 11

Acc #2
2 V 0 Del.

Acc #2
2 V 0.2Del.

#19

#19
1.24

91

B2-23

3
1.74
1000 PSI
100 # Flow

10 ms/Div @ RT

Acc #1
.2v cal

Acc #2
.2v cal

ON

15

B2-24

#2

1·24

Accel #1
.2 v s.dd.

Accel #2
.2 v 0.2dd.

Solenoid Volts

5 ms (0.0 sit)

2
1.2.7.7
1000 psi
no Flow

10 ms/Div @ ...

Accel #1
.1 V

Accel #2
.1 V

no
flow

B2-26

/3

APPENDIX B3

AIR MOTOR 70A-66

Air Motor 70A-66 is an axial-piston air motor that may be operated as either non-reversible or reversible with full power in either direction. This motor, see Figure B3-1, has high torque characteristics, and its 5 piston power impulse characteristics assure even torque at all speeds.
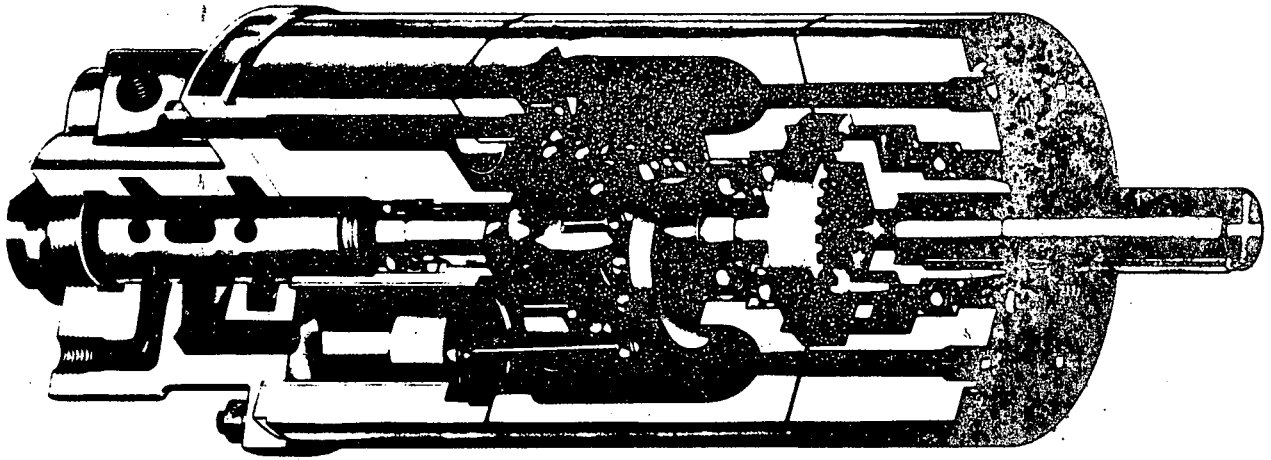
Figure B3-1. Axial Piston Air Motor

AIR MOTOR FUNCTION

This air motor functions to pneumatically drive or power machinery. It may be used in such diverse applications as rotating turntables, powering cranes, mixing paint, etc. It provides variable speed, reduces spark hazard, and cannot burn out. Ratings for this air motor at 90 psi are:

 a. Horsepower—1.9.

 b. RPM—315.

 c. Rated Free Speed RPM—605.

 d. Stall Torque—64 ft-lbs.

 e. Starting Torque—48 ft-lbs.

 f. Gear Ratio—5.8:1.

 g. Weight with Standard Shaft—26.5 lbs.

 h. CFM at Maximum Output—62.

 i. Maximum Overhung Load on Shaft at Stall—1000 lbs.
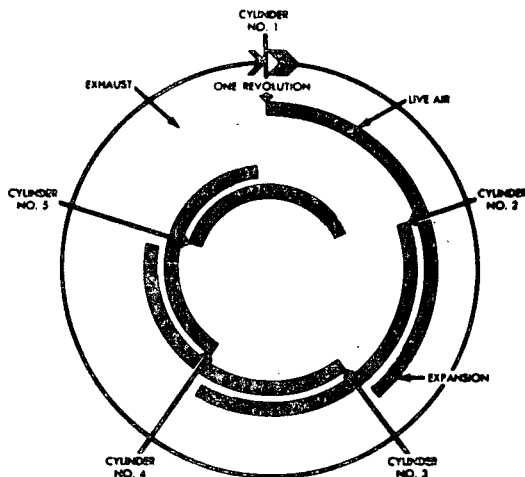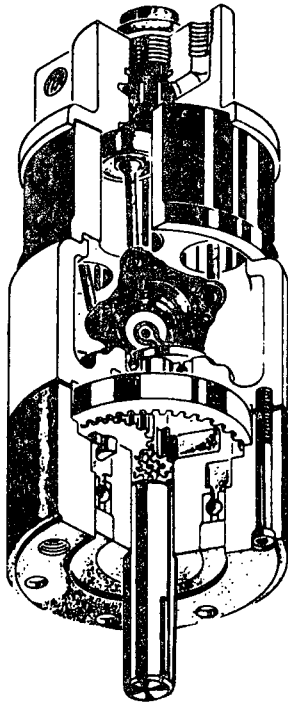
RIGID CONSTRUCTION of entire motor offers maximum usage during the long life of the motor.

GENEROUS SIZE SPINDLE BEARINGS allow a heavy overhung load on the spindle with no external spindle support.

PRECISION MACHINED PARTS insure a long service life for the motor with a minimum of maintenance.

COMPACT DESIGN of motor permits its use in close quarters and cramped installations where space is a limiting factor.

ENCLOSED CONSTRUCTION allows use in corrosive and dusty atmospheres. Motors perform satisfactorily when placed in high temperature areas.

SIDE AND END AIR INTAKE PORTS are provided on the 3 larger series of motors, permitting close quarter installations and giving added convenience for piping connections. Side ports only are provided on the smallest series.

AN INSPECTION HOLE AND PLUG is provided in the rear housing of the air motor for checking quantity and condition of lubricant.

FACE MOUNTING OF THE AIR MOTOR to a fixture with three bolts equally spaced, allows positioning of air connections and a positive mount without strapping—motor is readily removable for servicing or replacement.

MAXIMUM AMBIENT OPERATING TEMPERATURE is 200°F. MAXIMUM OPERATING PRESSURE is 100 PSI.

Power impulses for the five-piston motors are the same as those for the radial piston design. At least two pistons are on the power stroke at all times, providing even torque at all speeds.

Axial-piston air motors operate smoothly, with absence of vibration. The unique "wobble plate" and piston design perform smoothly at all speeds and working pressures.

SERIES
70A6

Series 70A-62, 64, 66—Single Geared

Series 70A6-29, 17, 10—Double Geared

70A-66

Model No.	Output at 90 PSI		Rated Free Speed RPM	Stall Torque Ft. Lbs.	Starting Torque Ft. Lbs.	Gear Ratio	Weight Lbs. With Standard Shaft	CFM At Maximum Output	Maximum Overhung Load On Shaft At Stall
	HP	RPM							
70A-62	1.9	1820	3500	11	8	—	26.5	62	1000 lb.
70A-64	1.9	535	1030	37	27	3.4:1	26.5	62	1000 lb.
70A-66	1.9	315	605	64	48	5.8:1	26.5	62	1000 lb.
70A6-29	1.9	152	290	130	96	11.9:1	42.5	62	1000 lb.
70A6-17	1.9	89	170	223	163	20.3:1	42.5	62	1000 lb.
70A6-10	1.9	54	100	370	269	33.6:1	42.5	62	1000 lb.

PISTON MOTOR
SIZE 70A-62, 70A-64, & 70A-66

ALTERNATE CONSTRUCTION

A-27137 MUFFLER

(1-3/8"-18 THD.) C-101-G NUT (6)

17748 PLUG

3/8" PIPE THD.

10237 BUSHING

A-17739 HEAD ASSEMBLY (ALUMINUM)

A-10226 DISTRIBUTOR

2VR-45 KEY 18439-1 RETAINING RING

2V-85 BEARING

2V-169 LOCK NUT

2V-272 WASHER

2V-189-1 GASKET

A-2V-1 CYLINDER

10027 GASKET

A-17605 BEVEL GEAR
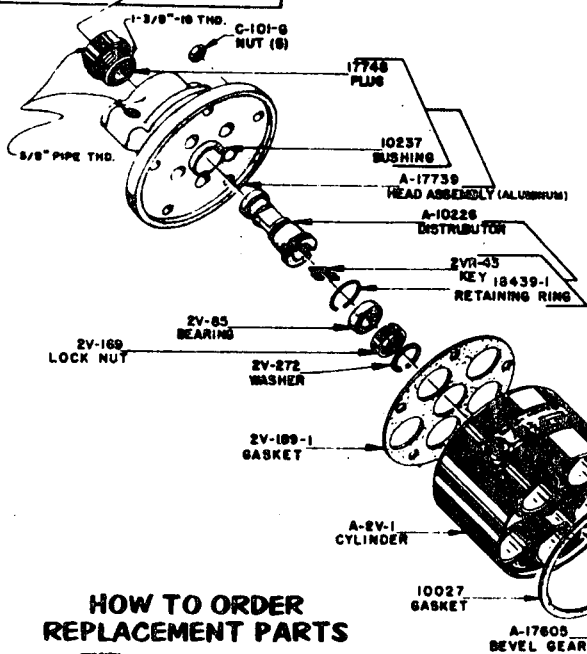
LUBRICATION
USE NO. A-5 OIL
INSTALL AIR LINE LUBRICATOR &
FILTER IN AIR LINE AHEAD OF TOOL
GREASE FREQUENTLY
USE NO. A-12377 GREASE

A-10058 DRIVESHAFT COMPLETE

2V-236 RETAINING RING

2N-92 STEEL BALLS (11)

A-17604 BEVEL GEAR

A-2V-2 PISTON ASSEMBLY (5)

8-135-Z ‡ SCREW

2V-172 SOCKET PLATE

18997 LOCK WASHER

8-108-A SET SCREW (5)

17996 PIN (5)

226-230 LOCK NUT

2V-225 OUTER BALL RACE

2N-93 STEEL BALLS (10)

A-10047 DRIVESHAFT

HOW TO ORDER
REPLACEMENT PARTS
SPECIFY:
1. QUANTITY
2. PART NUMBER
3. PART NAME

70A-66 MOTOR
18327 BEARING

A-10033 IDLER GEAR (2)

10032 PIN (2)

18321 GEAR CAGE

70A-64 MOTOR
18323 PINION GEAR

A-18322 IDLER GEAR (2)

18318 GEAR CAGE

18304 BEARING

18307 OIL SEAL

10026 GASKET

18364 BEARING LINER

27401 STUD (6)

A-18317 REAR HOUSING (ALUMINUM)

30775 GREASE FITTING

226-158 BEARING

IR-76 PLUG

70A-62 MOTOR
18319 GEAR CAGE

18324 DRIVING BLOCK

18320 RING

DP-120 PIN

10019-A RING GEAR

30775 GREASE FITTING

18316 FRONT HOUSING (STEEL)

8-119-S SCREW (6)

GREASE

18306-1 KEY

18326 KEY

1/8"-18 THD.

18319-A SPINDLE ASSEMBLY

‡ 507490 POWER UNIT

ALTERNATE CONSTRUCTION
FLUSH TYPE MOTOR
(GEAR CAGE FLUSH WITH FRONT HOUSING)

FOR 70A-62 AND 70A-64 USE 18318-1 GEAR CAGE AND 18319-1-A SPINDLE, WHICH INCLUDES 20569-1 KEY AND 18326 KEY.

FOR 70A-66 USE 18321-1 GEAR CAGE AND 18319-1-A SPINDLE, WHICH IN-CLUDES 20569-1 AND 18326 KEYS.

NOTE: FOR OTHER SPINDLES — SEE SECTION 70, PAGE 31.

‡ CHANGES MADE SINCE LAST ISSUANCE OF THIS SHEET

PC-1707

Exploded View, Figure B3-2
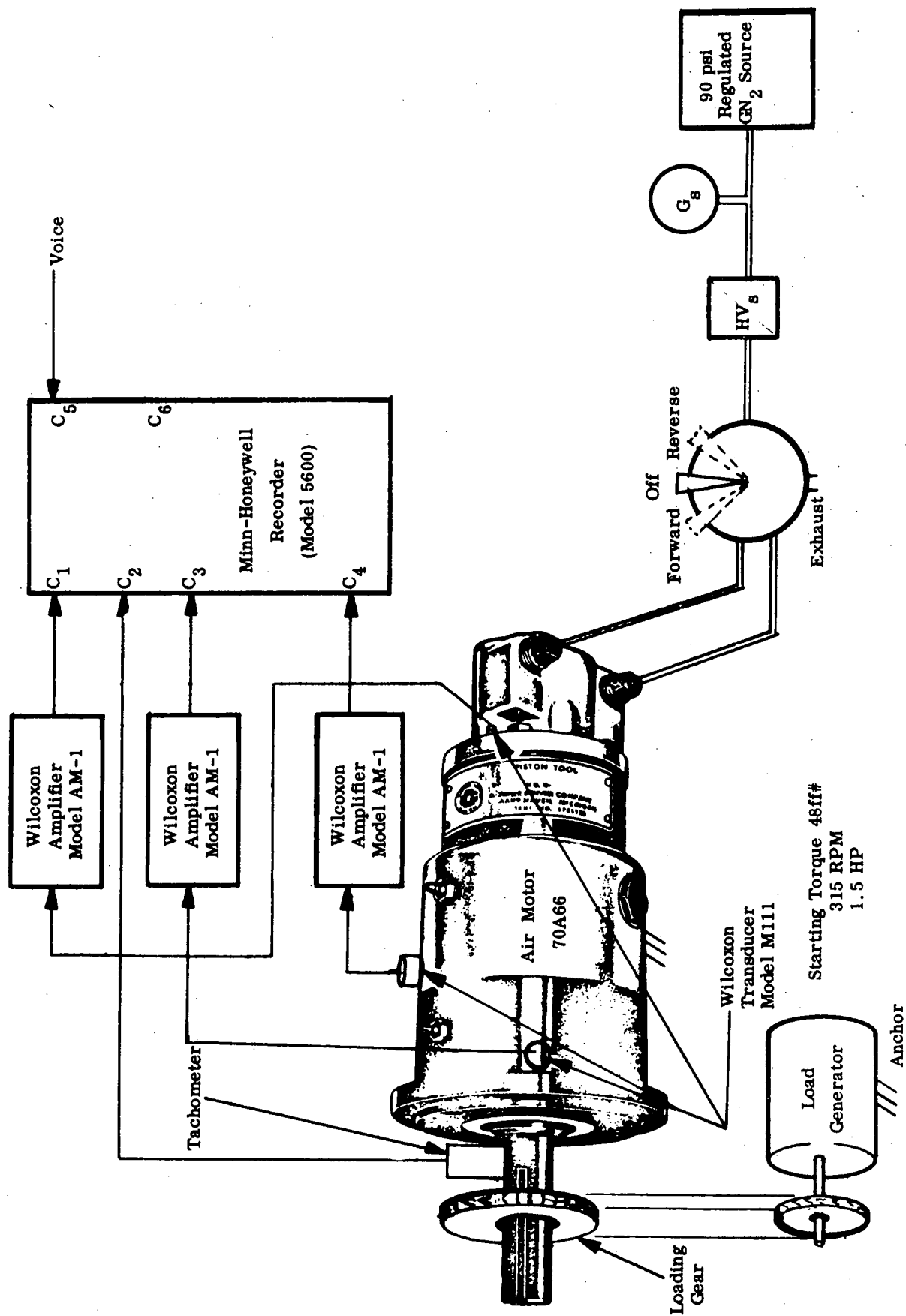
Figure B3-3. Air Motor 70-A66 Acoustic Test Mechanical and Electrical Connections

APPENDIX B4

BLOWER HF-P58032, SERIES 355KS

The blower is powered by a 200 volt, 3 phase, 400Hz, 3700 rpm motor delivering up to 1150 cfm and is of the type used for cooling in electronic cabinets.

CATALOG SHEET	50103-1C
REPLACES	50103-1B
FANS	5
PROPELLER	01
MODEL HF	03

YELLOW LABEL

TYPES 801-2-3

- **COMPACT • LIGHT • SELF-CONTAINED**
- **Size: 10.18″ x 8.12″ x 7.75″ APPROX. • WEIGHT: 3.5 - 8 LBS.**
- **50-60, 400 CPS • 1 PHASE OR 3 PHASE, ALL STANDARD VOLTAGES**
- **AVAILABLE FOR EITHER "PUSH" OR "PULL" AIRFLOW**
- **BUILT TO APPLICABLE MILITARY SPECIFICATIONS**

ROTRON INCORPORATED

TYPE CHARACTERISTIC
$N_s = 200,000$

MODEL HF • TYPES 801-802-803

WHERE TO USE

ROTRON MODEL HF fans are designed for flushing radio cabinets, instrument panels and transmitter cubicles. They meet the special requirements for such applications as high output, light weight, compact and self contained construction, low motor winding temperature use greased for life ball bearings, and do NOT have to be accessible for lubrication. Standard types cover 1700 and 3400 RPM speeds and air deliveries are per key graph at top right of this page. Audible noise level varies with shaft speed and pitch of the propeller chosen, which in turn govern pressure-building capacity.

For smaller fans refer to ROTRON MODELS NF, MF, and DFE. For similar fans not built to government specifications, refer to ROTRON CARAVEL FAN and GREEN-LABEL fan MODEL PF.

MOTOR

The induction motor is either three-phase or permanent split-phase capacitor type and is available with either A, F, or H insulation. The corrosion-protected case, which totally encloses the motor, is finned for maximum heat dissipation resulting in a minimum winding temperature rise. The motor operates on double-shielded, precision ball bearings which are greased for life and are carefully aligned for quiet, trouble free operation. The case and shaft are of die-cast aluminum and stainless steel respectively. Where "T Frame" motors are used (see Type Chart), a compact screw-type terminal block is fitted integrally into a recess in the motor case so that hookup cables can be run directly to the motor. Eighteen inch spiral-tracer, color-coded leads are supplied with "D Frame" motors. Motors meet applicable military specifications for ground, sea and airborne service. See applicable Catalog Sheet in Section C, "MOTORS". U.S. Patent Design 174,148. Other U.S. Patents Pending.

AIRFLOW

Complete air performance graphs, including winding temperature rise and watt input curves are given on catalog sheets following this page. All fans are available for either push FLOW "L" or pull FLOW "R" operation. The motor with propeller is permanently mounted on a venturi ring which is designed for efficient operation of both directions of airflow. This venturi ring, moreover, allows simple mounting of the complete assembly on a dustfilter housing or cabinet wall. No auxiliary parts like spacers or rings are required. For selection of propeller fans in general, see Application Note "SELECTION and APPLICATION OF PROPELLER FANS" in catalog section "ENGINEERING DATA".

VIBRATION

All motors used on MODEL HF fans are finely dynamically balanced. In order to minimize transmission of any residual vibration from motor or propeller to the mounting panel, the MODEL HFV fan can be specified which incorporates vibration isolation mounts between mounting spider and venturi ring. In case of external vibration or shock conditions (as encountered in most military applications) do not specify the MODEL HFV fans because resonant conditions may result in undue excursions of the fan motor. Model HF fans powered by TA3 or DA1 frame motors will pass government specifications for shock and vibration with standard venturis and motor mounting spiders. Units equipped with heavier DA2 or DA3 motor frames must be provided with heavier venturis (1/16" material thickness) and reinforced mounting spiders when extreme shock and vibration conditions must be met. The reinforced unit is designated as MODEL HFG. The reinforced spiders are shown on the lower part of Figure 2.

MATERIALS AND FINISH

Propeller and venturi ring are aluminum and anodized. The mounting spider is of steel and cadmium plated. Motors have aluminum

Motors covered by U S Pat Des 174,148   Other U S Patents Pending.

frames, corrosion-protected black enameled, and stainless steel shafts. Fans pass applicable government specifications for high humidity, fungus, and altitude operation. Special finishes on request. Phase-splitting capacitors, where required, are not normally furnished by ROTRON. On larger orders and on special request, such capacitors may be mounted directly on the motor frame. The optional screen guard is steel and cadmium plated.

ORDERING INFORMATION

- Specify Fan Type and Motor Series number by consulting Fan Type Chart on basis of available power supply and performance required.
- Specify flow direction, either Flow "L" or Flow "R". This is explained on the outline drawing that follows.
- Specify whether or not vibration isolator mounts are required. If required order Model HFV rather than Model HF
- Screen Guard (see drawing) is optional and must be specified if required
- Specify maximum and minimum temperatures and densities or atmospheric pressure.

EXAMPLE: Specify Model HF, Type AS-802, Flow L, Series 123JS, −55°C to 70°C, 14.7 ±2 PSIA.

ROTRON INCORPORATED
WOODSTOCK, NEW YORK 12498

6-69-10m

.08 ± .02

10.16 DIAMETER

MOUNT OVER 9.12 DIAMETER OPENING

10.00 DIAMETER

.081

2.50

"L"

SCREEN GUARD (Optional)
ORDER SEPARATELY
PART No. 18083-3

AIRFLOW "R"
AIRFLOW "L"

VIBRATION
ISOLATOR
(Optional)
MODEL HFV ONLY

2.75 OVER FINS

"T" FRAME

"T" FRAME
MOTOR CASE
(See Text Under "MOTORS")

FIG. 1

"T" FRAME

ROTATION

NAME-PLATE

TYPICAL SPIDER
AS NORMALLY SUPPLIED
MODELS HF & HFV
(See Text Under "VIBRATION")

8 MOUNTING HOLES
.180 DIAMETER
EQUALLY SPACED
ON 9.687 DIAMETER

NOTE: Drawing shows two different spiders on
one fan. Both top and bottom spiders
will be the same on any one model of
fan.

.081 or .18
(See Text Under "VIBRATION")

VIBRATION
ISOLATOR
(Optional)
MODEL HFV ONLY

10.16 DIAMETER

MOUNT OVER 9.12 DIAMETER OPENING

10.00 DIAMETER

.08 ± .02

2.50

"L"

AIRFLOW "R"
AIRFLOW "L"

3.75 OVER FINS

STANDARD LEAD
LENGTH 18"

"D" FRAME
MOTOR CASE
(See Text Under "MOTORS")

TYPICAL SPIDER
MODEL HFG
COMBINED WITH
.18 THICK VENTURI

(THIS CONFIGURATION IS ONLY
SUPPLIED WHEN CONDITIONS OF
HIGH VIBRATION OR SHOCK
ARE PRESENT)

(See Text Under "VIBRATION")

FIG. 2

"D" FRAME

ROTATION

NAMEPLATE

TOLERANCES	
2 PLACE DECIMALS	± .06
3 PLACE DECIMALS	±.010
(Unless otherwise Specified)	

———USE OF SCREENGUARD———
THE PERFORMANCE DROP CAUSED BY THE GUARD
IS APPROXIMATELY AS SHOWN BELOW. THIS DROP
MUST BE SUBTRACTED FROM THE FAN PERFORMANCE
CURVES GIVEN ON FOLLOWING CATALOG SHEET.

PRESSURE DROP
INCHES of WATER
.25 .20 .15 .10 .05

PRESSURE DROP
OVER
SCREEN GUARD

0   250   500   750   1000
AIR VOLUME - CFM

MODEL HF(V) FAN
TYPES 801-802-803

SHAFT SPEED

Figures given in the TYPE CHART on page 2 as well as on the nameplate are nominal only and generally refer to MAXIMUM CFM air delivery at sea level and at nominal line voltage and frequency.

DIMENSIONS

For dimensions and tolerances, refer to outline drawing except for such dimensions as are listed in this TYPE CHART under MECHANICAL.

WATTAGE AND CURRENT

Figures in this TYPE CHART are for nominal line voltage and frequency, and generally apply to the condition of MAXIMUM CFM and sea level operation. In case of 50-60 CPS motors, they apply to 60 CPS. In case of variable frequency motors, they apply to 400 CPS.

FREQUENCY RANGE

The line frequency range listed for variable frequency motors is necessarily arbitrary, because the range depends on acceptable variations in speed (air delivery) with frequency. Performance as a function of frequency can be adjusted by changes in the design of the motor winding. Rotron will design driving motors which will operate on odd frequencies as well as over special and extremely wide frequency ranges.

BEARING SHELF LIFE

Rotron military quality motors are built to operate under humidity conditions as specified in MIL-E-5272. When stored under high humidity conditions, however, the bearings will deteriorate. It is therefore strongly recommended that the fans and blowers not be subjected to more than six months of inoperative shelf life in humid climates and not more than one year in dry climates. Units properly packaged in sealed containers with a desiccant may be expected to withstand longer shelf life.

HOOK-UP

The first suffix letter immediately following the motor SERIES number listed in the accompanying TYPE CHART refers to the applicable wiring diagram found on catalog sheet C-1000 in Section C, MOTORS. Phase-splitting capacitor values, as may be required, are listed in this TYPE CHART.

CAPACITORS

Wherever phase-splitting capacitors are indicated in this TYPE CHART, these are not normally supplied by Rotron. Their values should preferably be held within a tolerance of ±10%, especially for 400 CPS and variable frequency motors. In selecting capacitors, due attention should be given to variations in capacity ratings with high and low ambient temperatures. Unless stated differently in this TYPE CHART, Working Voltage ratings are 220 VAC for 115 Volt lines and 330 VAC for 230 Volt lines. Oil-impregnated, canned, paper capacitors are recommended.

AIR DELIVERY

Figures in column AIR of this TYPE CHART represent actual amount of air moved at sea level standard atmospheric conditions per AMCA code.

MOTOR INSULATION

This TYPE CHART lists the NEMA classification for each motor. Motors with a different class of insulation than listed can generally be supplied. To obtain the actual maximum hotspot winding temperature for any unit, add the maximum ambient temperature to the WIND. RISE°C HOTSPOT reading obtained from the Performance Graphs immediately following this page, applying to the air delivery rate of the selected operating point on the performance curve. Limiting total winding temperatures are 105°C for Class A, 150°C for Class F, and 180°C for Class H insulation. The 105°C figure for Class A is conservative and could be extended to 115°C where the life of the equipment is not expected to exceed 2000 hours.

FAN TYPE CHART

BLOWER or FAN Type	MOTOR Frame	MOTOR Series	Volts	Phase	CPS	Cap. Mfd.	Nominal RPM	Insul. Class	Watt Input at Free Delivery	Line Amps at Free Delivery (At Lower Voltage)	Locked Rotor Amps.	Max. CFM	Total Net Lbs.	Dimension "L" Max. Vibration Isolators With	Dimension "L" Max. Vibration Isolators Without
KS-801	DA1	(12)	(12)	1	50-60	2.0	3400	(12)	50	0.52	1.5	510	5.0	6¼	6¼
LS-801	DA1	268AS	115	1	50-60	2.0	1750	A	25	0.26	0.62	260	5.0	6¼	6¼
AS-801	TA3	(1)	(1)	3	50-60	—	3250	(1)	41	0.3	0.80	480	3.5	6⅜	6⅜
BS-801	DA1	254JS	208	3	50-60	—	1750	A	30	0.25	0.61	260	5.0	6¼	6¼
PS-801	DA2	(4)	115	1	400	1.0	3750	(4)	95	1.25	2.10	540	6.0	6¾	6¾
PS-801	DA1	(2)	(2)	3	400	—	3800	A	106	1.8	3.2	560	5.0	6¼	6¼
KS-802A	DA1	(13)	(13)	1	50-60	3.0	3300	A	65	0.55	1.45	630	5.0	6¼	6¼
LS-802A	DA1	268AS	115	1	50-60	2.0	1750	A	25	0.26	0.62	330	5.0	6¼	6¼
AS-802A	DA1	(3)	(3)	3	50-60	—	3350	A	50	0.2	0.77	650	5.0	6¼	6¼
BS-802A	DA1	254JS	208	3	50-60	—	1750	A	30	0.25	0.61	330	5.0	6¼	6¼
PS-802A	DA2	(4)	115	1	400	1.0	3650	(4)	112	1.35	2.10	700	6.0	6¾	6¾
NS-802A	DA3	589AS	115	1	400	5.0	5875	F	390	3.7	12.0	1050	8.0	—	7⅞
PS-802A	DA2	(10)	(10)	3	400	—	3800	A	135	2.2	3.90	740	6.0	6¾	6¾
NS-802A	DA2	(14)	(14)	3	400	—	5650	F	250	2.45	8.0	1050	6.0	6¾	6¾
KS-802	DA2	(5)	(5)	1	50-60	4.0	3300	(5)	120	1.0	2.05	810	6.0	6¾	6¾
LS-802	DA1	268AS	115	1	50-60	2.0	1700	A	30	0.30	0.62	400	5.0	6¼	6¼
AS-802	DA2	(6)	(6)	3	50-60	—	3350	(6)	82	0.6	2.30	820	6.0	6¾	6¾
BS-802	DA1	254JS	208	3	50-60	—	1750	A	31	0.25	0.61	410	5.0	6¼	6¼
NS-802	DA3	(7)	(7)	3	400	—	5800	F	420	6.0	13.4	1400	8.0	—	7⅞
PS-802	DA3	(11)	(11)	3	400	—	3850	F	215	3.5	5.0	890	8.0	—	7⅞
KS-803	DA3	413AS	115	1	50-60	8.0	3350	A	165	1.3	3.0	1050	8.0	—	7⅞
KS-803	DA3	(8)	(8)	1	50-60	2.5	3300	(8)	165	1.5	3.7	1000	8.0	—	7⅞
LS-803	DA1	268AS	115	1	50-60	2.0	1650	A	35	0.34	0.62	500	5.0	6¼	6¼
AS-803	DA3	(9)	(9)	3	50-60	—	3350	(9)	144	1.0	4.0	1020	8.0	—	7⅞
AS-803	DA2	(6)	(6)	3	50-60	—	3100	(6)	130	0.75	2.4	950	6.0	6¾	6¾
BS-803	DA1	254JS	208	3	50-60	—	1700	A	43	0.25	0.61	550	5.0	6¼	6¼
AS-803	DA3	697AS	380	3	50-60	—	3380	F	144	0.31	1.4	1000	8.0	—	7⅞
NS-803	DA3	(7)	(7)	3	400	—	5600	F	680	7.5	13.4	1630	8.0	—	7⅞
PS-803	DA3	519AS	115	1	400	2.0	3600	F	285	3.3	5.0	1080	8.0	—	7⅞
PS-803	DA3	(11)	(11)	3	400	—	3700	F	295	3.8	5.0	1150	8.0	—	7⅞
KS-803	DA2	217AS	115	1	25	4.0	1450	A	43	0.415	0.43	440	6.0	6¾	6¾

(1) Specify choice of:

Motor Series	Line Voltage	Insul. Class
105JS	208	A
237JS	115	A
427JS	440	A
386JS	208	H

(2) Specify choice of:

Motor Series	Line Voltage
272WS	208
363WS	416
505WS	115

(3) Specify choice of:

Motor Series	Line Voltage
139JS	208
251JS	440

(4) Specify choice of:

Motor Series	Line Voltage	Insul. Class
391AS	115	A
450AS	115	F

(5) Specify choice of:

Motor Series	Line Voltage	Insul. Class
329AS	115	A
329BS	115/230	A
329CS	230	A
509AS	115	F
692AS	115	H

(6) Specify choice of:

Motor Series	Line Voltage	Insul. Class
123JS	208	A
190JS	115	A
197JS	440	A
197LS	220/440	A
344JS	208	F

(7) Specify choice of:

Motor Series	Line Voltage
267JS	200
337JS	115
372JS	416

(8) Specify choice of:

Motor Series	Line Voltage	Insul. Class
328AS	115	A
328BS	115/230	A
328CS	230	A
895AS	115	H
338AS	115	F
338BS	115/230	F
338CS	230	F
351BS	220/440	A

(9) Specify choice of:

Motor Series	Line Voltage	Insul. Class
154JS	208	A
196JS	115	A
207JS	440	A
538LS	220/440	A
246JS	115	F
266JS	208	F
353JS	440	F
931JS	208	H

(10) Specify choice of:

Motor Series	Line Voltage
270WS	208
277WS	115

(11) Specify choice of:

Motor Series	Line Voltage
561WS	115
594WS	200

(12) Specify choice of:

Motor Series	Line Voltage	Insul. Class
364AS	115	F
364BS	115/230	F
364CS	230	F
600AS	115	H
932BS	115/230	H

(13) Specify choice of:

Motor Series	Line Voltage
564AS	115
564BS	115/230
564CS	230

(14) Specify choice of:

Motor Series	Line Voltage
518JS	200
1028JS	115

ACCURACY

Curves below represent results of measurement of a typical sample and should be taken as nominal. Rotron will advise tolerance for a specific application. Allowance should be made for the effect of "channeling" of ball bearing grease.

FLOW DIRECTION

Note that 2 sets of graphs are given for each type of fan. The top set for FLOW L and the bottom set for FLOW R. For definition of flow see outline drawing.
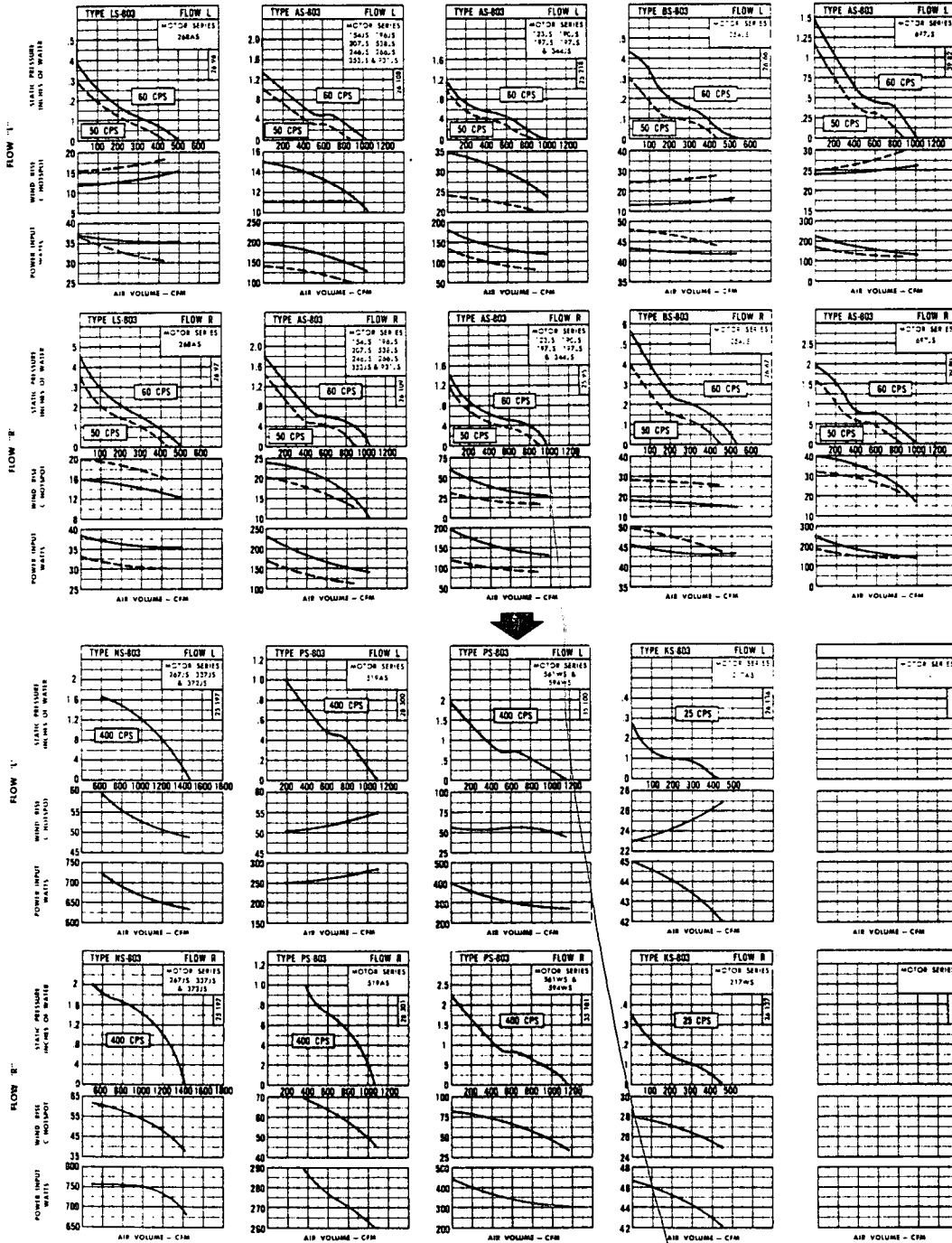
Component of Interest

B4-6

MOTOR HOOK-UP DIAGRAMS

ROTRON INCORPORATED
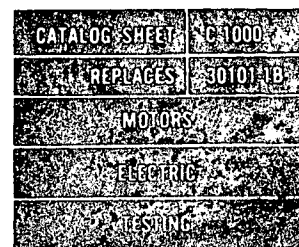
MOTOR SERIES NUMBER

Each type of ROTRON motor carries its own SERIES number (not to be confused with the motor serial number which identifies a single individual motor only). This number identifies its electrical characteristics. The motor SERIES number is found in the TYPE CHARTS on all ROTRON catalog sheets describing fans and blowers.

HOOK-UP IDENTIFIED BY SYMBOL LETTER

Motor SERIES numbers consist of 2 or 3 digits followed by two suffixing letters, e.g. 94AS, 295JS. The first letter corresponds to the symbol found in the first column of the chart below. It identifies the proper hook-up diagram. The second suffixing letter, if other than S standard denotes a mechanical modification from standard and reference should be made to a separate specification. If the motor nameplate does not show a motor SERIES number or if the SERIES number shown is followed by the suffixing letter X then the hook-up diagram is to be found by consulting either the ROTRON or the customer's specification and or outline drawing.

DEFINITION OF MOTOR ROTATION

Standard motor rotation is determined by viewing the leadwire or terminal block end of the motor. Wiring is dependent on motor rotation only.
If the motor SERIES number denotes other than a standard motor (e.g. 94A1 or 295J3); refer to either the ROTRON or customer's specification and or outline drawing.

TERMINAL CODING

Motors with LEAD WIRES are coded either by color or markers on the individual leads. Diagrams below give both types of coding.

FOR MOTORS WITH TERMINAL BLOCKS note the view or views of the terminal blocks in the chart below immediately at the right of the applicable hook up diagram. Select the view which corresponds to the type of terminal block found on the particular motor. Then note the location of the colored coding DOT on the view as well as on the motor. From this location the exact position of each of the terminals can be ascertained.

COLORED DOT
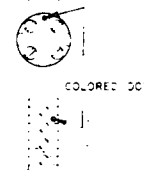
SINGLE VOLTAGE MOTORS — FOR DUAL VOLTAGE SEE REVERSE

*For "K" winding diagram current readings always refers to Red #1 or Green #2 leads or terminals.

For 3 phase motors all voltages are phase to phase.
115 230 or 220 440 indicates motors can be operated on either voltage.
3 phase designs can be supplied 3 wire ("J") or 4 wire ("Q").
Running capacitors are not supplied by Rotron.

3-70-2m

APPENDIX C

SBA COST OF IMPLEMENTATION

1.0 GENERAL

This appendix documents the rationale and assumptions which were made to estimate the cost of implementing SBA. The cost elements include development programs, detail design, manufacturing, testing, and computer programming. This cost estimate is based on implmenting SBA readiness assessment for an advanced space program, assumed equivalent in ground and flight hardware requirements to the Saturn V program.

2.0 DEVELOPMENT PROGRAMS

Developmental programs, in general, permit the analysis of a number of concepts on a limited number of test articles. The knowledge gained permits widespread extrapolation of developmental conclusions resulting in a higher probability of success at a relatively nominal cost. Based on an assumed labor rate of $3,000 per man month, the estimated cost summary for development programs is contained in Table C-1.

Table C-1

Developmental Programs Cost Summary

Development Program	Manpower (Man Months)	Hardware ($)	Total Cost ($)
Mechanical Component Selection Utilizing SBA	17	0	50K
Derivation of Mechanical Component Operating Parameters	25	75K	150K
Prototype SBA System Implementation	34	160K	260K
Total	76MM	$235K	$460K

3.0 DESIGN

Application of SBA mechanical readiness assessment in an operational form could begin now with some sacrifice in degree and sophistication. SBA application to advanced space programs which might utilize LC-39 will take one of two forms:

- Rework of existing mechanical components to add accelerometers.
- Replacement of existing mechanical hardware with the next generation hardware which will have a significant amount of built-in mechanical readiness assessment transducers and conditioning.

Evaluation of SBA implementation costs, even on a gross scale, will require many simplifying assumptions. Basic to cost estimates of this section is the approach that modification of existing components will precede the coming generation of mechanical components which will have built-in transducers/signal conditioning. The cost estimates are based on hardware designs which will be available in the 1973-74 time frame.

Additional assumptions include:

- Add-on SBA mechanical readiness assessment will be competitive in cost with components having built-in assessment capabilities, i.e., add-on readiassessment plus mechanical component cost will be equivalent to the cost of a component with built-in readiness assessment.
- The data bus philosophy will be implemented and operational for command and data transmission.
- SBA will be implemented to the extent that hardware is available off-the-shelf.
- The previously recommended development programs will be accomplished.
- The ground and flight hardware contains 20,000 mechanical devices, of which 20 percent or 4000 will have a criticality high enough to justify the implementation of mechanical readiness assessment.
- Of the 4000 components, 1000 are transient action components and 400 are cyclic. The remainder are flow noise devices which will not utilize the SBA technique.
- Each mechanical component (1400) will require two accelerometers.
- Detail design of system processing equipment is estimated to require six man years. See Addendum A for assumptions on sizing of processing equipment.
- Detail design of an instrumented mechanical device, including component level logic and transducer integration, is estimated at one man week per mechanical component.
- Systems engineering (reliability, logistics, and configuration management) is estimated to require 20 percent of the design cost.
- Preparation of test specifications, end item specifications, test procedures, interface drawings, schematics, and functional drawings additional cost due to SBA one third man days per instrumented LRU.
- A labor rate of $15 per hour is estimated as an average for design personnel.

The estimated design cost, using the above rationale, is tabulated in Table C-2.

Table C-2

Design Cost Summary

	Total Cost ($)
Basic Design of System Processing Equipment	180K
Detailed Design of Instrumented Mechanical Devices	840K
Other Design-Related Functions (Specification, etc.)	63K
Systems Engineering	204K
	1.29M

4.0 MANUFACTURING

The manufacture of SBA mechanical readiness assessment components such as transducers, conditioners, cabling, and processing components presents no insurmountable problems. Making mechanical readiness assessment a viable philosophy will, however, require ingenuity relative to size, weight, cost, and power consumption.

Manufacturing cost includes:

- Hardware Costs
- Receiving Inspection
- Fabrication
- In-Process Inspection
- Functional Test
- Calibration
- Packaging for Shipment
- Removal and Reinstallation of Mechanical Devices.
- Functional Checkout

The following assumptions were made relative to the manufacturing costs:

- Each accelerometer and associated conditioning hardware will cost $600.
- Processing equipment will cost $734,000 in hardware. See Addendum A for rationale.
- Each transducer and associated hardware will require 1/2 man day for receiving inspection and calibration and 1/2 day for installation.
- Cabling and miscellaneous hardware will cost $100 per mechanical component.

- Integration of the signal conditioning, transducers, and mechanical components will require three man days per component.
- Functional testing, in-process and final inspection, cleaning, and packaging for shipment will reqire one man day per instrumented mechanical device.
- Installation and functional checkout of each mechanical device will require 2/3 day.
- Manufacturing labor is estimated at $10.00 per hour.

The estimated manufacturing costs are contained in Table C-3.

Table C-3

Manufacturing Cost Summary

Hardware	Total Cost ($)
Transducers	1.68M
Processing Equipment	.734M
Miscellaneous Hardware	.22M
Total	2.554M
Fabrication/Assembly	
Processing Equipment	.09M
Inspection/Calibration/Installation of Transducers	.22M
Mechanical Device Integration	.34M
Final Testing Through Shipment	.11M
Installation and Functional Checkout	.08M
Total	.84M
Manufacturing Total	3.394M

5.0 TESTING

5.1 QUALIFICATION TESTING

Component testing should provide a uniform, direct, and prudent method of obtaining engineering confidence in ground and airborne hardware at a minimum cost of time and money. The qualification test as a part of an overall testing program will enhance the effectiveness of SBA implementation. For the advanced space programs, the qualification test program will be of prime importance.

Qualification by testing as opposed to qualification by usage will be required initially for a number of components used to implement mechanical readiness assessment based on the fact that mechanical readiness assessment will be applied initially to the most critical components. With experience, new transducer, condition, and processing hardware will be qualified with less sophisticated, less costly tests based on similarity to previously qualified components.

Components/assemblies which will require qualification testing include:

- Accelerometers
- Signal Conditioners
- Processing Equipment

As a cost effective means of qualification testing, many different components can be tested as overall assemblies. At longer range, the components having SBA mechanical readiness assessment fully implemented will require qualification testing to include all mechanical readiness assessment hardware. The qualification tests should be significantly less expensive than testing on a piece-part basis.

Only the cost of performing the test and preparing the test report is included in this estimate. Facilities, special hardware, and data file maintenance cost is not included, based on the presumption that these items are a necessary part of any space program.

5.2 TESTING TO ESTABLISH DISCRIMINANT LIMITS

Implementation of SBA mechanical readiness assessment will require identification of normal signature and specific limits (go, no-go, and caution) for each mechanical component.

5.3 TESTING COST SUMMARY

The following assumptions form the basis for the testing cost summary.

- Testing to determine the baseline signature for the 1400 mechanical components will be $1K each.
- The number of components and estimated cost for qualification are shown in Table C-4.

Table C-4

Qualification Test Requirements

Component	Number	Testing Cost ($ Each)
Transducers and Associated Conditioners, Power Supplies and Cabling	20	5K
Processing Equipment	5	5K

- Cost of hardware to be tested is estimated at $124K for two of each component to be qualified with no salvage value (see Table C-5).
- Hardware for parameter limit testing will be selected from GFE stores and will eventually be installed for operational use.
- Qualification testing of 20 transducers and 5 processing equipment black boxes will be adequate to qualify the remainder by similarity.
- A well appointed test and qualification laboratory is assumed to exist.

Table C-5

Testing Cost Summary

Qualification Testing	Total Cost ($)
Hardware Costs	124K
Transducers	100K
Processing Equipment	25K
Total	249K
Baseline Testing	
Hardware Costs	None
1400 Components at	
$1K Each	1,400K
Processing Equipment	180K
Total	1,580K
Testing Total	1.83M

5.4 PROGRAMMING COST

In order to accomplish the functions envisioned for the SBA readiness assessment processing, software programs will be required for calibration, parameter limits, self-checks, and mechanical device readiness evaluation. Four man years of programming effort are estimated (see Appendix C) at cost of $120K.

5.5 COST SUMMARY

Potentially, there are systems areas where significant cost savings would accrue with the implementation of SBA, though these are difficult to express quantitatively. Some of the considerations which could reduce the cost differential between implementing and not implementing SBA include:

- Maintenance when required versus a set time between overhaul based on a failure prediction capability.
- Early detection of incipient failures, thus reducing repair costs.

- Implementation of SBA will reduce the dollar and time costs required to verify hardware ready to support an operational exercise.
- Automatic readiness assessment will reduce data reduction and fault identification time based on evaluation by exception as opposed to a lengthy review of all data to determine component health.
- The sustaining cost of a complex having automatic self-contained readiness assessment at the LRU level will be less costly to maintain and operate.

A summary of the estimated SBA implementation cost is shown in Table C-5.

Table C-5

Summary of SBA Implementation Costs

	Total Cost ($)
Development Programs	460K
Design	1,290K
Manufacturing	3,394K
Testing	1,830K
Programming	120K
Cost of Implementing SBA	$7,094K

ADDENDUM A

PROCESSING EQUIPMENT CONFIGURATION ESTIMATIONS

1.0 GENERAL

The assumptions made for sizing and costing the SBA processing equipment are included below. Estimates are made first for cyclic components and next for transient action components. In this processing equipment sizing exercise it is assumed that data bases are predetermined and programmed into the processor in advance. No dynamic real-time update of the trend data base is assumed. The processed go, no-go, and caution digital outputs can provide automatic interlocks or be displayed via the KSC Launch Processor System.

2.0 CYCLIC ACTION COMPONENT ASSUMPTIONS

- 400 components, 2 transducers each
- All cyclic components will require summation analysis signal enhancement; therefore, sync signal is also required by Processor
- Average cyclic component speed is 4 rps
- 100 revolutions must be assessed on the average (25 sec)
- Transducer frequency range is 75 kilohertz; however, information to be processed will be contained in four 200-hertz bands
- Status of components required every 30 minutes
- 1000 samples per second required of each of 4 filtered signals for each transducer
- 50 per cent of components will be operating at any one time (200 components)

A block diagram of a processing system configuration capable of handling cyclic action component processing based on the preceding assumptions is shown in Figure A-1.

The approximate cost of this system is:

		Total 1 System	Total
Hardware		$96K	$576K
• Multiplexer	$ 6K		
• Frequency Sync	40K		
• Mixers	1—6K		
• Filters	2—4K		
• A/D Converter	2—4K		
• Buffer	1K		
• Processor	15K		
• Processor Memory (8K)	8K		
• Disc Memory	5K		
• Peripheral In/Out Equipment	10K		
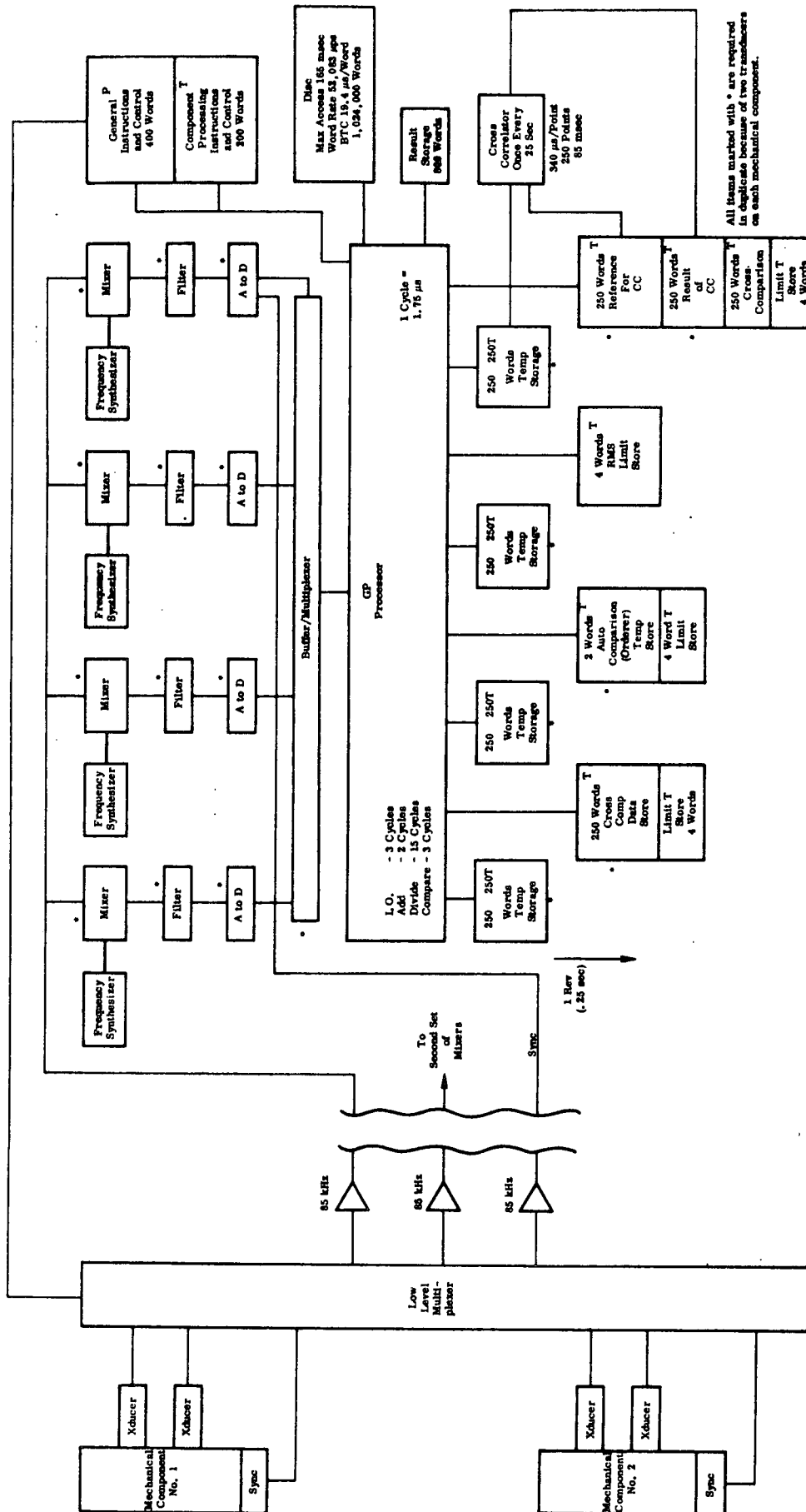
M. C. Meekins
General Electric,
Advanced Technology Engineering

Figure A-1. Data Handling and Processing

		Total 1 System	Total
Design	2 Man Years	$ 60K	$ 120K
Manufacturing/System Assembly	1/2 Man Year	15K	75K
Testing	1 Man Year	30K	150K
System Engineering	4 Man Years	18K	24K
Programming	8 Man Years	24K	60K
		$237K	$1.05M

Additional notes pertinent to Figure A-1 and the sizing of SBA data handling and processing include:

Collection (Every revolution each component)

Transfer In	8 inputs × 250 data points × 3 cycles	= 6,000
Additions	8 inputs × 250 data points × 2 cycles	= 4,000
Divisions	8 inputs × 250 data points × 15 cycles	= 30,000

$$40,000 \times 1.75 \mu s = 70 MS$$

BTC 1200 words In 24 MS + 30 MS = 54MS ⎫ Cannot overlap with processing
BTC 1200 words Out 24 MS + 30 MS = 54MS ⎬ or data collection
—————— ⎪ Can overlap with data sync
108MS ⎭

Data Sync Time 250 MS

Processing (Every 100 rev. each component)

Orderer	2 inputs × 250 words × 2 comparisons × 3 cycles	= 3,000 cycles
RMS	2 inputs × 250 words × 31	= 15,000 cycles
Correlator Inputs	2 inputs × 2 signals × 250 words × 3 cycles	= 3,000 cycles
Correlator Outputs	2 × 250 × 3 cycles	= 1,500 cycles
Comparisons	8 signals × 250 words × 4 comparisons × 3 cycles	= 24,000 cycles

$$
\begin{aligned}
&47,000 \text{ cycles} \\
&\times 1.75 \\
&= 82.25 MS
\end{aligned}
$$

This system can monitor and process needed data for one component every +60.8 seconds; therefore, the one system can cycle through 200 components in 3 1/2 hours. This system needs a multiplier of approximately 6 to achieve complete cycle in 1/2 hour; therefore total cost is estimated at $1.05M.

3.0 TRANSIENT ACTION - COMPONENT ASSUMPTIONS

- 1000 transient components to process
- 48 components operating at any one time
- Time domain signals to process
  - 24 components at any one time
  - 45 MS maximum actuation time

- 5 MS minimum actuation time
- Accuracy 5 per cent of reading
- 2 transducers per component
- Analyze after one execution
- Time domain type of signal processing
  - 24 components
  - RMS
  - Time to first peak
  - Time from first peak to silence
  - Time between internal peaks
  - All of above compared to limits
- Frequency domain type of signal processing
  - 24 components
  - 4 frequency bands, 2 kHz each
  - RMS (1)
  - Cross comparison (2)
  - Peak to peak (1)
- Sequence of events for monitoring transient data
  1. Based on input from checkout computer, set low level multiplexer to monitor desired transducer.
  2. Based on availability of analog recorders, select the particular recorder and tracks to receive signal. Erase these tracks.
  3. Read reference information from disc into working memory based on next component to be processed.
  4. Select the appropriate synthesizer frequencies for the next component to be processed.
  5. Sequence high-level multiplexer to next component to be processed.
  6. Initiate A-to-D's when the sync signal is received.
  7. Input all data into memory.
  8. Process data and output result.
  9. Monitor input from control computer for next measurements, and repeat cycle beginning at step 1 or 5 until all measurements have been processed.

A block diagram of a processing system configuration capable of handling transient action component processing based on the preceding assumptions is shown in Figure A-2.

The approximate cost of this system is:

			Total
Hardware			$158K
• Multiplexers	51K		
• Frequency Sync	40K		
• Mixers	1—6K		
• Filters	3—2K		
• Analogue Recorders	20K		
• A/D Converters	3K		

- Buffer 1K
- Processor 15K
- Processor Memory (8K) 8K
- Disc Memory 5K
- Peripheral In/Out Equipment 10K

Design	2 Man Years	60K
Manufacturing/System Assembly	1/2 Man Year	15K
Testing	1 Man Year	30K
System Engineering	4 Man Years	12K
Programming	2 Man Years	60K
	Total Cost Estimate	$335K
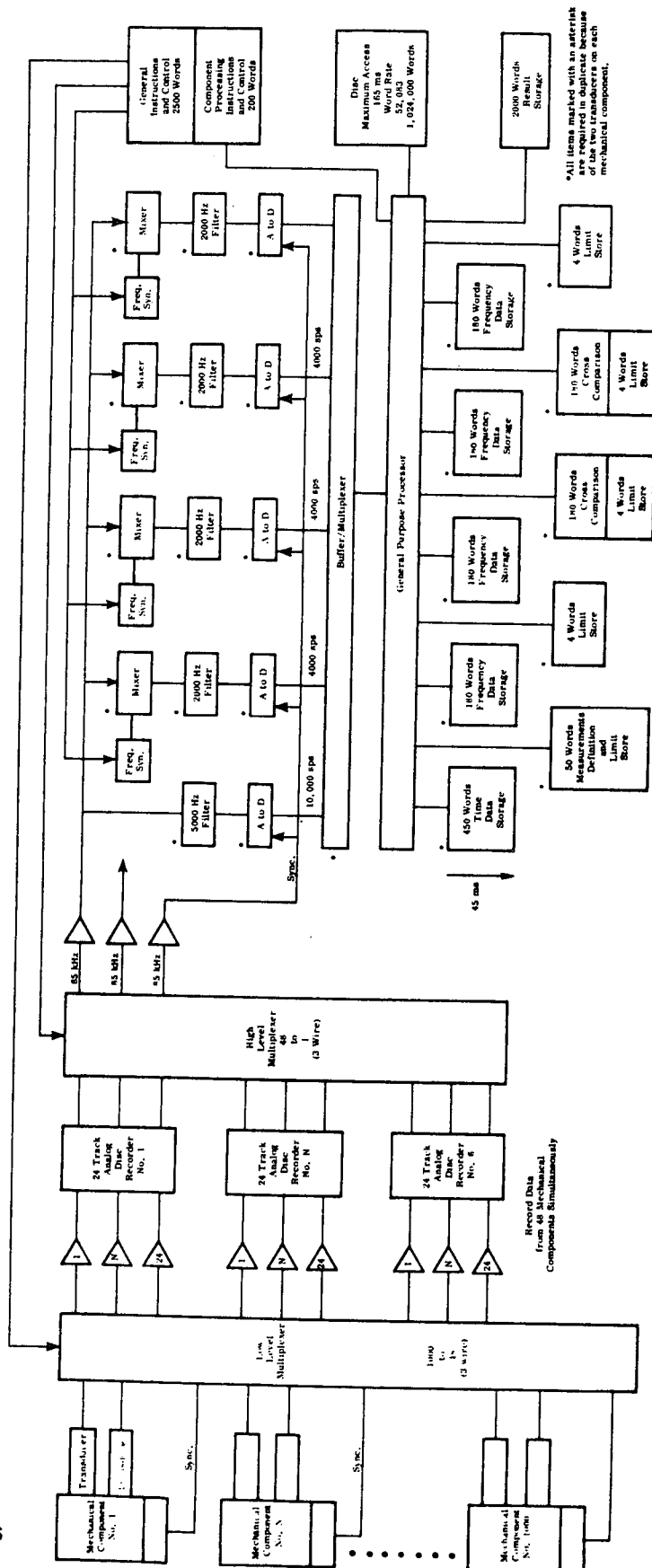
M. C. Meekins
General Electric,
Advanced Technology Engineering

Figure A-2. Data Handling and Processing—Transient Action Device

APPENDIX D

STRUCTURE BORNE ACOUSTICS HANDBOOK

D/.D-D

TABLE OF CONTENTS
APPENDIX D

STRUCTURE BORNE ACOUSTICS HANDBOOK

CHAPTER 1

INTRODUCTION

It has become increasingly apparent that mechanical devices lack the real time readiness assessment and fault prediction capability required for future space programs. Structure Borne Acoustics (SBA) is a non-destructive test technique that has shown significant promise for alleviating this problem. This checkout technique lends itself to reducing checkout time, simplifying maintenance procedures and reducing manual involvement in the checkout, operation, maintenance, and fault diagnosis of mechanical systems.

As a sophisticated non-destructive checkout technique, Structure Borne Acoustics is an infant. While some laboratory work has been accomplished and limited operational implementation in rudimentary form has been achieved, this checkout technique remains relatively unused. One key reason is that it requires the merger of such diverse technologies and disciplines as Statistics, Acoustic Signature Prediction and Analysis, Mechanics, Spectral Analysis, Summation Averaging, Electronic Data Acquisition and Computer Processing, all of which must be related to mechanical device nominal and failure mode operations.

This handbook has been compiled by the General Electric Company (Contract NAS 10 - 7788) to bring together, under one cover, information covering those elements of the various technologies essential for understanding and implementing "Structure Borne Acoustics". A general solution methodolgy has evolved which, it is felt, will materially aid system designers and other users in the implementation process. The text will define and clarify terminology, describe the mechanical component analysis methodology and measurement system, and discuss acoustic testing and interpretation of measurement data.

CHAPTER 2

WHAT IS STRUCTURE BORNE ACOUSTIC TEST TECHNIQUE?

2.1 INTRODUCTION

"Structure Borne Acoustic Test Techniques" will be defined in this chapter.
In addition, some fundamental acoustic principles will be reviewed and the
relationship of Structure Borne Acoustics (SBA) to mechanical device
readiness assessment will be established. The intent is to cover these
subjects only to the depth required for an understanding of the
methodology recommended for implementing the Structure Borne Acoustic
test technique. Ample references are provided in Appendix A for those
interested in backup information to the material presented and Appendix B
contains pertinent definitions.

2.2 ACOUSTIC PRINCIPLES

The science of acoustics includes the generation, transmission, reception,
absorption, conversion, detection, reproduction, and control of sound.
Noise is a sound whose character can be defined and whose properties can be
measured. Sound or noise in a true physical sense is a vibration of particles
either in a gas, a liquid, or a solid. These vibrations or pressure alter-
ations act as traveling waves. As illustrated in Figure 2-1, sound distur-
bances are three-dimensional traveling waves having amplitude, frequency
and velocity. The behavior of these sound waves can be mathematically
described by conventional wave theory.
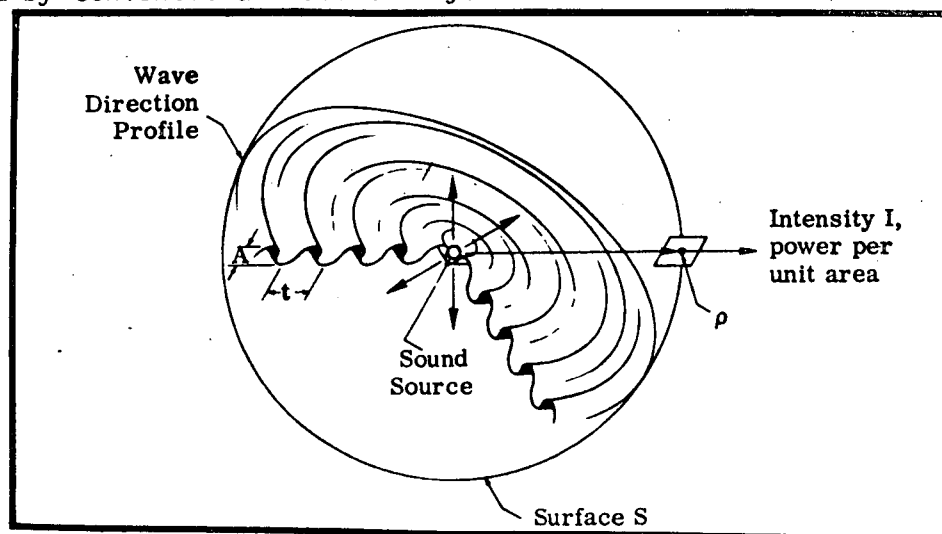
Figure 2-1. Sound Source Radiation

2.2.1 SOUND/VIBRATION INTENSITY AND LOUDNESS

The intensity of a wave at any point in space is defined as the amount of energy passing perpendicularly through a unit area at this point in unit time. Figure 2-1 shows this relationship pictorially. The intensity can be expressed in watts/m^2, or in any other appropriate units. The intensity of the sound received from any source depends upon the rate at which the source emits energy, upon the distance of the pick up transducer from the source, upon the transfer medium, and upon the reflections which the waves undergo from the surrounding objects. If the size of the source is small in comparison with its distance from the observer and if no reflection or absorption takes place, the intensity of the sound at any place will vary inversely as the square of its distance from the source, but this is rarely the case with sound waves. In terms of the sound wave, it can be shown that the intensity depends upon the square of the amplitude of vibration of the particles in the wave and upon the square of its frequency.

The loudness of a sound is a sensation experienced by an observer, and although loudness is related to the intensity of the sound, the relationship between the two is not a simple one. Waves in air may be detected by the normal human ear if their frequencies lie between about 20 to 20,000 Hertz and if their intensities are within a certain range; the range of intensities audible to the ear also depends on the frequency of the wave. Figure 2-2 shows the range of frequencies and their intensities which is perceived as sound by the normal human ear; the intensity of the wave is plotted along the y-axis, while the frequency of the wave is plotted along the x-axis. One scale shows the intensities in watts/m^2. Another scale shows the intensities in terms of the pressure changes in the wave; since the pressure in a wave varies sinusoidally, the effective or root mean square values of the pressure changes are used. The range of intensities to which the ear is sensitive is about a trillionfold.
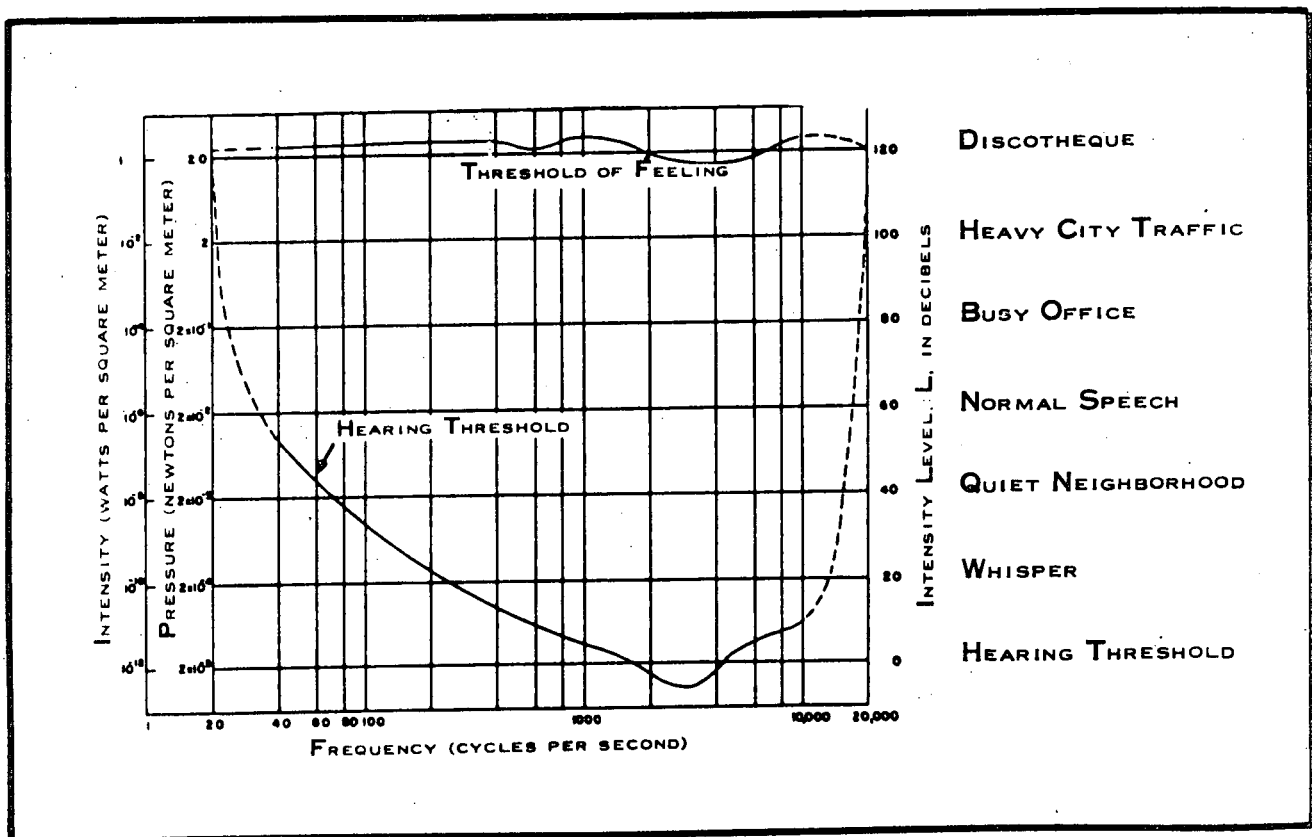
Figure 2-2. Sound Intensity and Loudness Relationships

Because of this large range of intensities, a logarithmic scale has been adopted for expressing the level of intensities of sound, taking the zero level at about the limit of audibility of sound. The intensity level B of a sound is defined as

$$B = 10 \log \frac{I}{I_0} ,$$

where I is the intensity of the sound and I_0 is the zero level of intensity which is taken aribtrarily to be equal to 10^{-12} watt/m^2. The intensity level B is expressed in decibels (db). Thus, if a sound has an intensity $I = 10^{-10}$ watt/m^2, the intensity level is

$$B = 10 \log \frac{10^{-10}}{10^{-12}} \text{ db}$$

or

$$B = 10 \, (\log 100) \, db,$$

from which

$$B = 20 \text{ db.}$$

Sound levels have been measured at various places under a variety of conditions. For example, inside a busy office the sound level is about 80 db, while the sound level of a whisper in a quiet room is about 20 db. Figure 2-2 also presents some common comparative sound levels.

2.2.2 FREQUENCY BANDS

In practical application, the noises encountered are rarely pure tones. They are rather a jumble of sounds ranging from low frequency roars to high frequency screeches. In order to measure this composition of noises, a frequency analysis is made which displays the sound energy distribution over the noise frequency range. This analysis is made with filters that sub-divide the sounds over the entire audible range into standardized frequency bands, permitting one to measure the pressure levels of only the sound within each subdivision. The filters derive their name from the fact that each one spans an octave; that is, the upper frequency limit is twice the lower limit, as shown in Figure 2-3. Sound levels in each octave are measured in decibels, and are referred to as Octave Band Levels.

For more detailed analysis of the distribution of sound energy as a function of frequency, narrower bands are used. One popular division is to split the octaves into three parts (1/3 octave bands). For special applications, as will become apparent in this handbook, still narrower bands of frequency must be analyzed to capture needed discriminant information.

BAND DESIGNATION (CENTER FREQUENCY)	BAND LIMITS
	11300 Hz
8000 Hz	
	5650
4000	
	2830
2000	
	1415
1000	
	707
500	
	353
250	
	176
125	
	88
63 Hz	
	44 Hz

Figure 2-3. Octave Bands

2.2.3 STRUCTURE BORNE SOUNDS

Structure borne sounds include all noise propagated through structures which generate their own vibration or sound signals through active motion of component parts. The Structure Borne Acoustic test technique is limited to the evaluation of this type of sound. Air propagated sound is excluded because of high attenuation and extremely low penetration at any metal interface. Also, air propagated sound has greater variability due to factors such as temperature, air density, and humidity that are impractical to control in a launch checkout environment.

2.3 STRUCTURE BORNE ACOUSTICS AS A METHOD OF ASSESSING MECHANICAL DEVICE READINESS

It is well recognized that to achieve high and predictable reliability for a mechanical system, it is not sufficient just to build it from high quality components. Many defects may be initiated first during assembly or during qualification tests. Such defects, which are not connected to component quality, reduce the overall system reliability. It is essential, therefore, that effective methods be available for non-intrusive checkout of a completely assembled product from the outside, before it is finally accepted. But high reliability of a product may only solve part of the problem. What is really desired is high availability, i.e., short total down-time for maintenance or repair as compared to effective operating time. There are two general areas, final component or system checkout and early fault detection, where effective diagnostic and readiness assessment techniques can significantly increase total availability. In both cases, the central problem is to evaluate internal conditions through external measurements, without disturbing the normal operation of the tested equipment.

Obviously, external detection of internal defects presents new problems compared to conventional component testing and inspection. This is particularly true for mechanical defects. Internal cracks, loose bolts, worn bearings, etc., are no longer open for visual inspection or direct measurement. Therefore, an information carrier is needed to transmit the internal information to the external evalualtor.

Sound and vibration are excellent information carriers in mechanical structures. The fundamental mechanical events which occur in operating mechanical devices, such as rolling, sliding, impacts, etc., all produce sound of some kind, which tells the experienced listener much about the internal condition.

Listening is really one of the oldest of all evaluation methods, basically because it does not require any instrumentation at all. A mechanic listens to an engine to determine its condition; or he might hold a screwdriver against a bearing housing to detect a malfunction in that particular bearing. Direct listening without special instrumentation is extremely useful for early malfunction detection in many cases. Very often changes in sound signatures precede the actual performance deterioration of machinery, which can be detected through other means. The sound from an automobile engine for example, usually tells about a faulty valve long before it is detectable through oil pressure and power output changes.

However, this kind of intuitive evaluation is more an art than a science. It requires a certain skill, which often is very high, on the part of the listener and the result is not amenable to quantitative definition. To make acoustic signature evaluation really valuable as a modern screening or failure prediction tool, much had to be added in terms of problem definition and mechanized evaluation.

A significant amount of work has been done (see Literature References, Appendix A) to advance the science of acoustics, mechanical signature analysis, and digital electronics during the past decade. This progress has made it possible to now formulate a methodolgy of which enhances the practicality of larger scale implementation of Structure Borne Acoustics to achieve Mechanical Systems Readiness Assessment.

2.4 STRUCTURE BORNE ACOUSTICS-A NON-DESTRUCTIVE TEST TECHNIQUE

The total non-destructive evaluation or test technique for assessing the status of a mechanical device includes the method of stimulating the device, the response resulting from the stimulation, the transducer for communicating the response, and the hardware and software used for data processing and evaluation. Figure 2-4 depicts the interrelation of these elements.
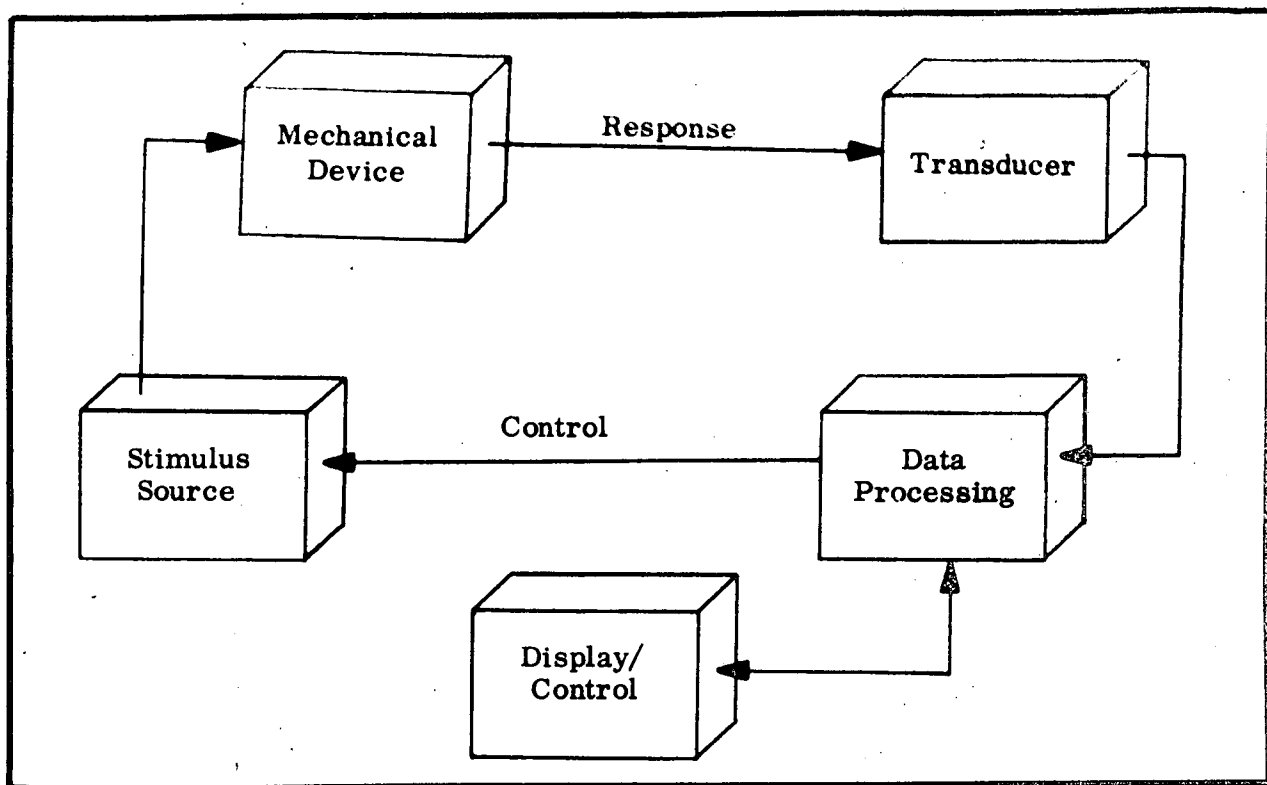
Figure 2-4. Elements of a Non-Destructive Test Technique

The definition of Structure Borne Acoustics as used in this handbook in-
cludes all of these elements of a non-destructive test technique. It in-
cludes detecting and converting mechanical device noise into an electrical
signal which is then processed, interpreted, and presented in such a form
to provide go, no-go, or caution status of the mechanical device. This
complete process is referred to as "Structure Borne Acoustics."

CHAPTER 3

MECHANICAL DEVICES AND STRUCTURE BORNE ACOUSTICS (SBA)

3.1 GENERAL

Structure Borne Acoustics as defined in Chapter 2 is a technique which can be applied to most noise producing mechanical devices. However, SPA, used indiscriminately, will result in undue complexity and cost with questionable gains in the capability for readiness assessment and condition monitoring of mechanical systems. Therefore, the implementation of Structure Borne Acoustics should be based on due consideration of cost, complexity (usually closely related) and adaptability of the technique to the readiness assessment requirements of the specific mechanical device. Consequently, prior to implementation of SBA, the applicability of SBA to the readiness assessment problem must be evaluated.

It is this consideration which will be examined in this chapter. Guidelines will be provided which will identify those mechanical component applications where SBA can provide sensitive, selective, economical, and perhaps otherwise unobtainable diagnostic capabilities.

3.2 MECHANICAL DEVICE CATEGORIZATION

3.2.1 GENERAL
Categorization of mechanical devices into groups of similar characteristics, either acoustically or mechanically, is necessary in order to define the elements of SBA technology applicable to different devices in more specific terms. The categories which will be defined and examined are:

o   Mechanical system, device identification.
o   Active and passive mechanical devices based on physical characteristics.
o   Active and passive components based on acoustical characteristics.
o   Cyclic machinery, flow noise and single transient generators.

Table 3-1   LC-39 Mechanical System/Mechanical Component Matrix.

3.2.2 ACTIVE/PASSIVE DEVICES

A study[*] of Saturn V Support, Facility, Launch Vehicle, Spacecraft and Mechanical Ground Support Equipment Systems has shown that over 20,000 mechanical devices were employed for this program. The distribution by mechanical system and component type is shown in Table 3-1.

A review of mechanical component symbology, (per MSFC-STD-162A, Figure 3-1) shows that mechanical components can be placed in two categories:

      1.   Active mechanical

      2.   Passive mechanical

Active components are "items that have a measurable output or influence upon the performance of the system." Mechanical components having moving parts would, in general, be classified as active mechanical components. Passive items such as pipes, bleed plates, and couplings were not tabulated.

Acoustical signature analysis techniques have been applied to a number of problems in the areas of product assurance and "on-condition" maintenance, (i.e., maintenance upon detection of an incipient fault). Application of these techniques have been generally resolved into two component categories - active and passive.

An Active Component is one which, through normal operation, generates a vibration or sound signal which can be correlated with internal operation/condition.

A Passive Component is one which must be stimulated, vibrated, or impacted to produce a sound signal. This technique is useful for determination of structural integrity, detection of loose particles, internal cracks, loose fits, etc.

This handbook is addressed toward active component acoustical signature analysis. Active systems which have been investigated through acoustic techniques include many kinds of machinery and components such as combustion engines, gear transmissions, pumps, fluid valves, and ball bearings. All generate their own sound signature during operation so that fault detection through listening becomes passive.

[*] Addendum A, Section I, Reference 32
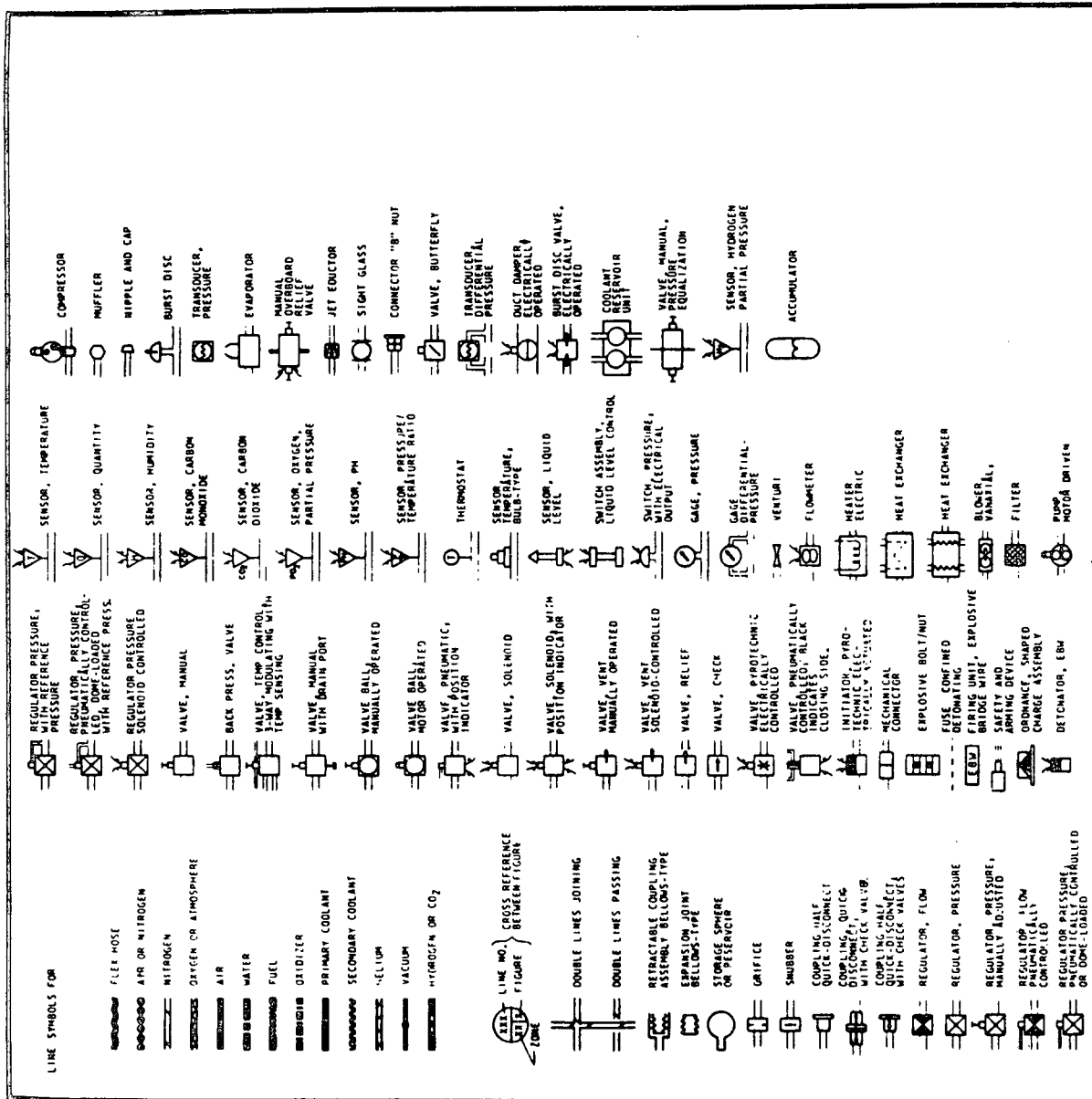
Figure 3-1   Mechanical Device Symbology

3.2.3 CATEGORIZATION BY ACOUSTIC CHARACTERISTICS

In the discussion of active component analysis, it is convenient to separate components into three groups:

- Cyclic machinery (e.g., engines, transmissions)
- Flow noise generators (e.g., pumps, boilers)
- Single transient generators (e.g., valves)

Different characteristics in the signature generation process have resulted in different analysis methods for the three groups.

Cyclic Machinery - In cyclic machinery, the operational events repeat at prescribed intervals. For example, in a four-stroke engine, the repetition period is two revolutions of the crankshaft. It would be logical then to use a detection method which enhances all features in the raw vibration signal that repeat every two revolutions, and discard everything else. Sound and vibration data recorded during the operation of engines, bearings, and generators are complex signals usually containing a high background signal level.

Digital summation techniques have been found to be an effective tool for detecting many internal malfunctions in cyclic machinery. This technique is predicated on the fact that a particular acoustic peak, through its location in a summed vibration signal and knowledge regarding engine kinematics, can be related to a particular event in the engine, resulting in a highly selective technique.

Flow Noise Generators - Fluid in a dynamic state produces sound due to motion of fluid in a pump, boiling in a reactor, motion through a chemical process, etc. Sound, traveling easily through a fluid, can propogate information about a condition at a point to where the information can be detected by an acoustic sensor.

Sensor data can be analyzed in real-time, producing a spectral analysis of the studied signal, with a very high time resolution such that a three dimension frequency - amplitude - time display is obtained. This display permits a study of the spectral content versus time.

<u>Single Transient Generators</u> - This third group of active components includes relays, valves, etc., which have a short work cycle and usually generate impact transients while operating. Depending upon the particular operating characteristics of the device, either time domain or spectral analysis, or both, may be applied to these devices.

Having once secured the component acoustic signature, there are a number of discriminatory techniques which can be utilized in conjunction with or rather than signal summation and spectral analyses.

3.3 READINESS ASSESSMENT PROBLEM

There are over 20,000 mechanical components located at Complex 39 in Saturn V ground and flight hardware. Future manned space programs such as the Shuttle are expected to require a comparable number of similar mechanical components. Based on reliability, effect of failure, cost, complexity, and the present state-of-the-art, it is clearly impractical to instrument all these devices for readiness assessment. Therefore, a rational selection process, based on these considerations must be established.

Having once established those devices for which some form of readiness assessment is required, identification of the assessment technique to be implemented must be determined. Structure Borne Acoustics is one of a number of non-destructive test techniques expected to be applicable to readiness assessment requirements of future space programs.

Operational usage of acoustic information requires identification of the significant device parameters which characterize normal and abnormal operation and applying (in most cases) numerical limits as a basis for Go, No-Go, or Caution decision. For example, bearing noise is a device parameter which is closely related to device condition. Go, No-Go, and Caution decisions can be made based on bearing noise established through testing or from trend information developed from on-line equipment.

The designation Go, Caution, and No-Go, as used above to indicate compoent status will occur frequently in this handbook and are defined as follows:

GO — The component is fully operational and no degradation has been detected.

CAUTION — The component can perform the intended function within operational limits but performance degradation has been sensed.

NO-GO — The component is not capable of performing within normal operational limits.

3.4 DETERMINATION OF STRUCTURE BORNE ACOUSTICS APPLICABILITY

3.4.1 COMPONENT CRITICALITY

The first readiness assessment question which must be faced for an operational mechanical system, is "which are the more critical components in this system?" This, of course, presumes that the system is of some criticality and that a reasonable readiness assessment budget exists.

Techniques of some rigor exist which will guide the designer in identification of component criticality on a relative basis. Considerations involved in the ciriticality determination include:

- Potential effect of mechanical device failure in the relevant failure modes.
  - Effects descend in severity from loss of life, mission scrub to no adverse effect.
- Probability of the most severe effect occurring for each relevant failure mode.
- Probability of failure for each mode.
- Time in which the considered failure mode and effect hold true.
- Failure rate of the mechanical device.

KSC-STD-122 provides a methodology for integrating these considerations and providing a quantitative result - criticality number. Comparison of the criticality numbers obtained for the various parameters, e.g., failure mode 1 vs. failure mode 2, provides guidance as to the most critical combinations. Comparison of the criticality numbers for two components will identify the more critical of the two.

3.4.2 STRUCTURE BORNE ACOUSTIC SELECTION

Having established the components which require some form of readiness assessment, the next question is, "What type of assessment should be implemented?"

Advantages/disadvantages to consider when evaluating SBA as an assessment technique include:

Advantages:

- Technique is non-intrusive.
- Output may be automated.
- No couplants are required.
- Access to only one surface is required.
- Provides remote and continuous surveillance.
- Dynamic rather than static flaw detection.
- Permanent record of event status can be obtained.
- Equipment is reasonably easy to operate.
- Equipment is portable.
- Large amount of developmental work already accomplished. The result of this work can be directly applied to solution of the Mechanical Readiness Assessment problem.
- Signal processing techniques are available which permit discrimination between needed acoustical information and undesirable background noise.
- Availability of noise and vibration transducers with adequate frequency selectivity, bandpass configurations, and sensitivity ranges.

Disadvantages:

- Part geometry and mass influences test results; therefore, unique data interpretation required for each different component.
- Must establish reference data (Go, No-Go, Caution parameters) in order to make proper interpretation from test data.
- Transducers must be placed on part surface.
- For active structure-borne acoustics, part must be operating.
- Extraction and processing of characteristic signals from noise background is complex.

3.4.3 SBA APPLICABILITY

Readiness assessment through SBA techniques has application to all cyclic components, a significant portion of the transient action components and limited application to flow noise generators.

An examination of SBA by mechanical device acoustic category has shown the following:

Flow Noise Generators - At any given point in time, flow noise in a pressure regulator, for example, is a function of down-stream pressure which can cause a flow from zero to a maximum. Therefore, knowledge of the downstream pressure is satisfactory for readiness assessment purposes making SBA instrumentation redundant. This, plus the absence of noise producing interactions within flow noise devices, limits the application of SBA to flow noise generators.

SBA techniques do have application to the detection of internal leakage, but, to be useful, the detection threshhold must be at least 1cc/minute.

Transient Action Components - Considerable information regarding the readiness of transient action devices may be obtained from the SBA techniques. The basic amplitude domain data (accelerometer output vs. time) can be readily processed to obtain (using a solenoid valve for descriptive purposes) valve response time, either actuation or deactuation. Timing information for this characteristic can be taken from voltage application (or removal) to the acoustic impact generated at the end of stem travel.

Solenoid valve operation - actuation, deactuation, and response time may also be obtained from a talk-back switch. If this were the only information desired, the switch rather than SBA would be the obvious answer. However, it is expected that SBA will ultimately be able to provide leakage information to the 1cc/minute level. This would make SBA a much more attractive form of readiness assessment for solenoid valves and, generally speaking, transient action devices as a component category.

Spectral analysis of acoustic data provides a time vs frequency plot and displays amplitude in a form similar to intensity modulation. Figure 3-2 shows such a plot of solenoid valve actuation and deactuation. The first dark vertical band is due to the application/removal of the actuation voltage, the second vertical band of the deactuation trace is due to the position switch opening and the dark vertical band on the right is the stem to seat impact. Note the valve body ringing in both plots at approximately 11 KHz. This resonance was predicated by the mathematical analysis.

Cyclic Components - Structure-Borne Acoustics has wide applicability to cyclic component readiness assessment. SBA has capabilities which are economical and practically unobtainable by any other assessment technique.

3.6 SUMMARY

Summarizing the methodology for choosing Structure Borne Acoustics over conventional forms of mechanical component Readiness Assessment:

    a. Assure that the component is an active mechanical device.

    b. Assure that the component is of a criticality which justifies readiness assessment.

    c. Establish that conventional instrumentation is inadequate.

    d. Determine that the specific discriminant(s) (measurement parameters) are amenable to SBA techniques.

Valve Deactuation

Frequency
(K Hertz)

48 40 32 24 16 8 0
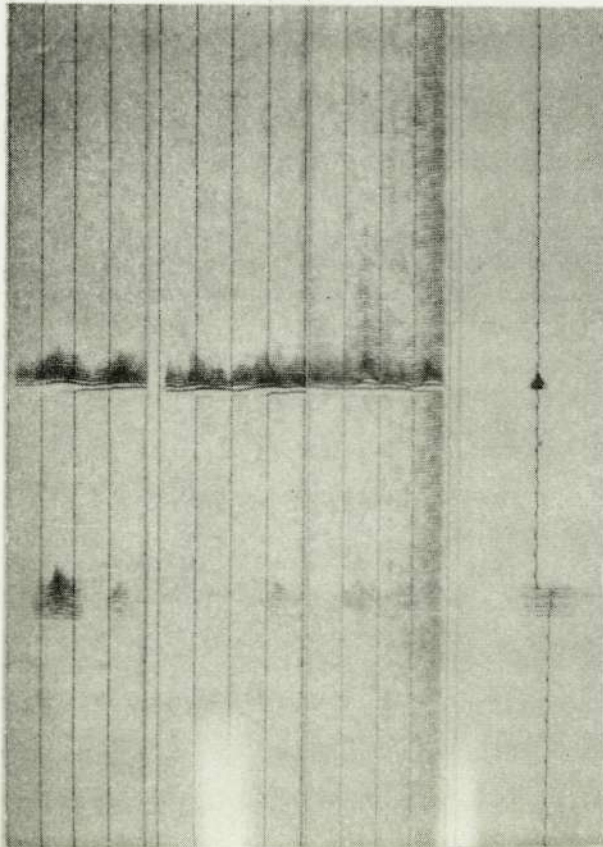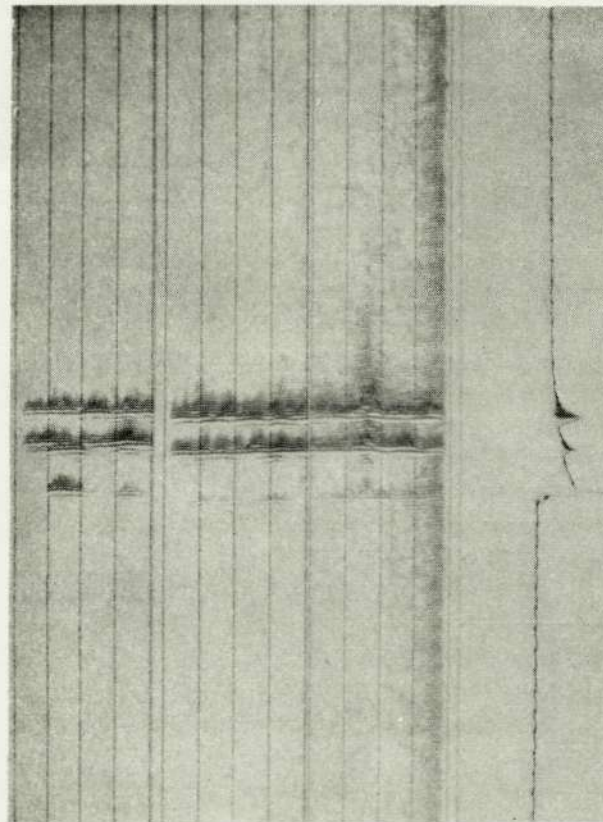
Valve Actuation

Figure 3-2   Modulated Spectrograms of Solenoid Valve Operation

D3-11/2

CHAPTER 4

MECHANICAL COMPONENT ANALYSIS

4.1 GENERAL

The SBA methods which may be used vary within a wide range. It is not a question of developing any particular sound analysis technique or instrumentation; rather, it is to use all that modern electronics has made available, including digital computer techniques.

The problem is to detect an internal defect while it is still small and its characteristic sound or its signature is hidden by sound from many other sources. Therefore, a selective technique must be developed in each application to extract from a complex sound or vibration signal some characteristic feature, or discriminant, which is highly correlated to the internal condition under study. This means a technique with the ability to sort out "False Alarms", including high background levels, and thereby reliably reveal a very small signature change.

It becomes the central problem to find this most effective discriminant in each application. Several approaches are possible.

One is entirely statistical. If a sufficiently large sample of signatures from good and malfunctioning units is available, it is possible to evaluate a large number of discriminants and through a correlation program and select the one most effective. The success of this approach depends entirely upon a good statistical sample. In most cases, such a sample is difficult to obtain.

A second approach, which forms the basis of the analysis methodology recommended in this handbook, is based on understanding the process by which a particular signature is generated and transmitted through a structure. This usually requires a thorough study of the mechanics of the equipment to be investigated so that a model for normal and abnormal signatures can be established. Once this is done, an analysis method with a good chance of success can be selected and then optimized experimentally.

This approach offers the outstanding advantage that only a small number of tests is required. Valuable also is the fact that, if a partly effective method has been found, the theoretical knowledge gained enables one to predict how the method must be changed to improve it.

Experience has shown that the key requirements for success are:

1. Understanding the mechanics of the equipment generating the signals, the failure modes, and failure mechanisms.
2. Understanding the process by which normal and malfunction signals are generated and propagated and predicting the resulting acoustic signature.
3. Correct selection of a responsive transducer.
4. Based on Requirements 1 and 2, correct selection of a technique which extracts the desired malfunction signature from the raw vibration data.

The first two requirements constitute mechanical component analysis and will be examined in this chapter. The remaining two requirements are treated in later chapters.

4.2 COMPONENT DESCRIPTION

In the beginning phases of implementing the SBA technique, knowledge of the component can significantly reduce the time frame for implementation. This is accomplished by elimination of unnecessary data collection and false starts through a thorough engineering analysis and verification of analytical work by pre-operational testing. As knowledge is gained from analysis, testing, and operational experience, testing can be further reduced by examination of only those unique characteristics of each device.

Source documentation which may be used for component evaluation and analysis is available in many forms as indicated in Table 4-1.

System Functional Drawings	Specifications
System Schematics	Operating Records, Logs
Installation Drawings	Environmental Records
Interface Control Documents	Technical Manuals
Operation & Maintenance Manuals	Failure Reports, Summaries
Failure Effects Analysis	Studies Relating to Mechanical Systems
Operation Procedures	Vendor Data, Technical Reports
Launch Mission Rules	Kennedy Approved Parts Lists
Test Procedures	Component Operational Profile
Test Reports	

Table 4-1   Component Source Documentation

4.3 OPERATIONAL ANALYSIS

4.3.1 COMPONENT OPERATION

The component to be acoustically instrumented must be examined in detail to establish the physical interactions which take place not only during active motion of internal elements, but preceding and following internal flow, motion of internal elements and the forces which produce this motion.

Considerable insight into component operation is possible through correlation of component test procedures (of the type used for component checkout following overhaul) vs. what takes place during checkout and adjustment. Test procedures of this type specify those parameters of significant value in determination of component condition as well as specifying nominal values of flow, pressure, temperature, operating time, leakage, position, et.al. These values form the basis for Go, No-Go, and Caution parameter values which must be obtained by the SBA techniques, perhaps in conjunction with other system instrumentation.

The purpose of this analysis is to:

o Provide an intuitive "feel" for component operation.

o Assist in the identification of noise-producing interactions.

o Assist in the correlation of acoustic signature with the physical operation of the device.

o Provide insight into potential failures and the effect of failure upon the acoustic signature.

4.3.2 INTERACTIONS CONTRIBUTING TO ACOUSTIC SIGNATURE

A composite listing of interactions within mechanical devices which contribute to the overall acoustic signatures follows:

o Medium Flow - e.g., hydraulic oil flow through a flow control valve.

o Activation Medium Flow - e.g., GN_2 flow causing an LH_2 valve to operate.

o Switch Activation - e.g., a solenoid valve talk-back switch closure.

o Background Noise - Provided by adjacent interactions, flow, impacts, machinery operation.

o Surface-to-Surface Interfacing - e.g. ,rolling of bearings, relative motion of two contacting surfaces (sliding), impacts produced by sudden, forceful surface-to-surface contact.

o Body Ringing - Produced by impact forces within the component.

o Electrical - Produced by vibrating solenoid turns or core laminations.

o Air in the flow or actuating medium - e.g., pump cavitation.

o Cold Shock - e.g., chilldown of cryogenic piping.

Using again, for illustration purposes, the example of the solenoid valve (See Figure 4-1) (75M08825-3), the mechanical interactions which contribute to the acoustic signature during actuation are:

o Impact of the armature (17) against the coil and core assembly (26).

o Armature (17)/Plunger (27) contact.

o Plunger (27)/Switch (28) contact.

o Stem (30)/Nylon Seat (34) impact.

o Secondary ringing of valve body (36)

o Flow

In addition to the above, some background noise is expected.

D4-4
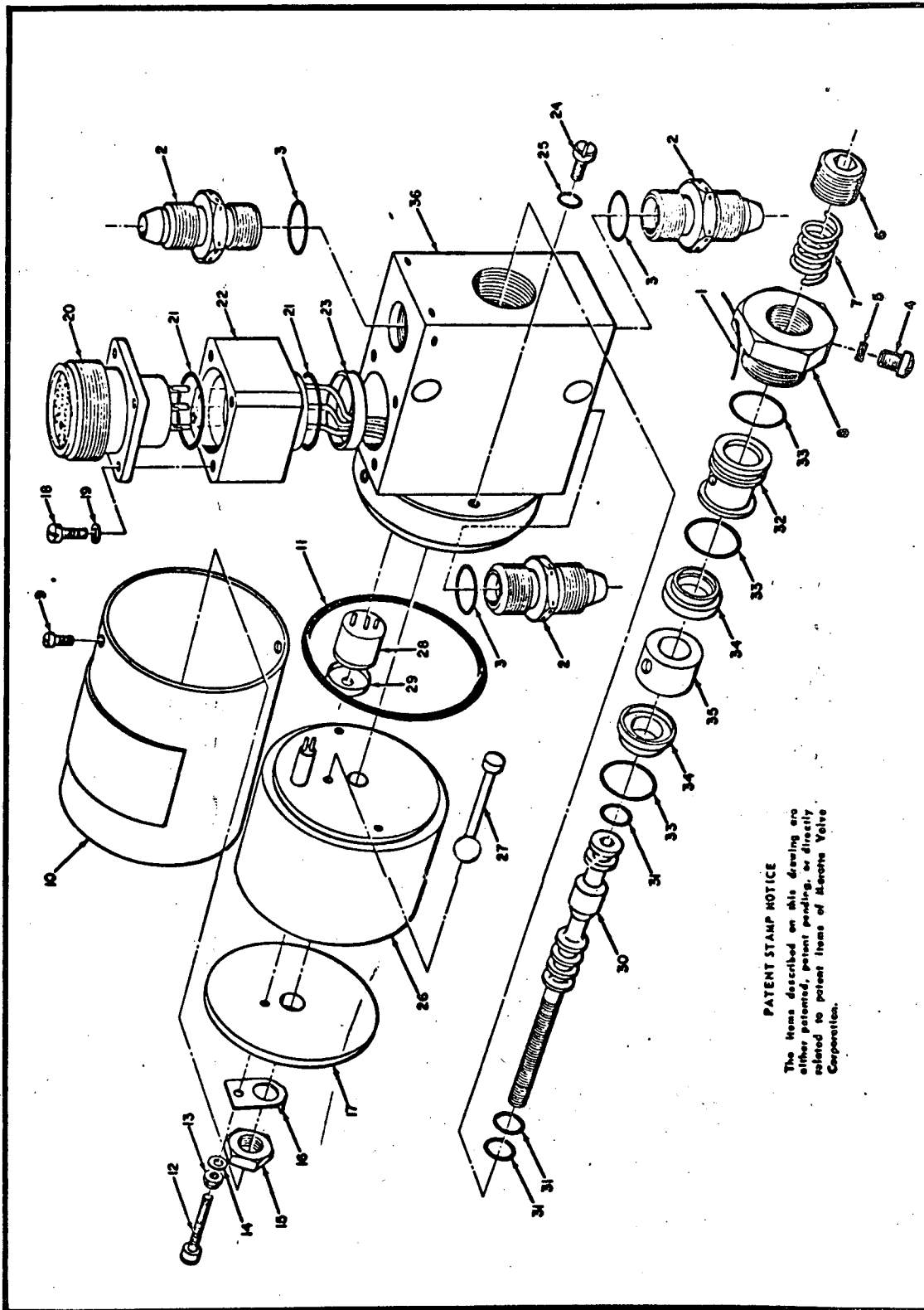
Figure 4-1. Solenoid Valve (Sheet 1 of 2)

4.4 COMPONENT ANALYSIS

4.4.1 MATHEMATICAL ANALYSIS

Analysis of components, particularly those cyclic in nature, require mathematical treatment in order to understand the relationships of the internal noise producing interactions. For example, the 70A-66 (reference Appendix B3) motor is a complex device with many ordered interactions taking place. For each rotation of the output shaft, the following interactions must be related in order to understand the acoustic signature obatined:

- o Piston excursion
- o Swash plate rotation
- o Gear meshes
- o Air intake exhaust cycles
- o Bearing ball rotation

Mathematical analysis also provides preliminary filter frequency requirements which will allow display of a specific aspect of component operation; e.g., a gear mesh frequency.

It is in the analysis of ball bearings where mathematical techniques have reached the highest degree of sophistication. Computer programs developed at the General Electric R&D Center provide, based on physical characteristics of the ball bearing:

- o Acoustic frequency and relative amplitudes for a range of normal (no defect) bearings
- o Repetition rate of transients for inner race, outer race and rolling element defects
- o Frequency and relative amplitudes for defects including:
    - Off-size rolling elements
    - Misaligned outer race
    - Out of round outer race
    - Misaligned inner race
    - Out of round inner race
- o Frequencies for in-plane flexural vibrations of the outer ring.

A KSC report (Addendum A, Section I, Reference 38) contains a mathematical analysis for two mechanical components - solenoid valve 75M08825-3 and pressure regulator 75M08831-1 which illustrates the process. These analyses, performed prior to acquisition of test data, were instructive but did not contribute as much as was initially expected. In general, it was concluded that a mathematical treatment of this form is necessary when frequency domain data must be related to internal component reactions.

4.4.2 FAILURE ANALYSIS

The first step in failure analysis requires the acquisition of historical failure data for the specific component and for generically similar data. From this data, a rather comprehensive summary of failure information can be obtained. For the purposes of this discussion, the following definitions are important:

Operational Effect - As a result of failure, is the component in a Go, Caution, or No-Go condition.

Failure Mode - The form in which a component failure is manifested, e.g., fails to operate, sluggish operation, leaks internally, etc.

Failure Mechanism - Identifies the component piece part which malfunctions and the specific problem. e.g., Valve stem mechanically binding.

Failure Cause - The basic anomaly which produced the failure mechanism e.g., corrosion, contaminated, low input voltage, etc.

Three readily available sources of failure data are:

o NASA KSC Failure Data Retrieval System - A typical computer output is shown on Figure 4-2. Unsatisfactory condition reports (UCR) listed on the printout are available within KSC.

o FARADA - (Failure Rate Data) provides general failure rate data, failure modes by percent of total failures. A sample page is shown as Figure 4-3.

o Malfunction Investigation Reports - Prepared by KSC SO-LAB-1 when laboratory analysis of component failure is desired. These reports can be correlated with UCR numbers.

Other excellent engineering analysis reports exist in the form of:

o Failure Mode and Effects Analysis (FEMA) provided by various reliability organizations.

o Vendor provided analyses and reports.

Figure 4-2

KSC DE-SED-2 UCR Tabulation

```
UCR P#?-?-?-='75M08825', LIST P#&PN&R#&MFD&LOC&VEH&FSD&DD
REQUEST QUEUED
PG     1 11/09/71  *NRN*  VERB: LIST.  OBJ: P#='75M08825'.
       PART-NUMBER             PART-NAME          REPORT-#
    MFG-DESC          LOCAT VEHICLE        FUN-SYS-DESC
          DEFECT-DESC


75M08825-3                    SOLENOID VALVE                KSC430733
  MAROTTA SCIENTIFIC    ML2    509     SWING ARMS - MECHANICAL
     INPROPER OUTPUT




** A TOTAL OF 000001 RECORD  MET QUALIFICATIONS. **
ELAPSED TIME >  19.55 SECONDS.
END OF REPORT
REL P#?-='75M08825', LIST P#&PN&R#&MFD&LOC&VEH&FSD&DD
REQUEST QUEUED
PG     1 11/09/71  *NRN*  VERB: LIST.   OBJ: P#='75M08825'.
       PART-NUMBER                    PART-NAME          DOCUMENT-NO
       MFG-NAME          LAUNCH-COMPLEX VEHICLE
          FUN-SYS-DESC                   DEFECT-DESC

75M08825                    SOLENOID VALVE                KSC318195
  MAROTTA VALVE CORP        LC39        AS501
     N2                        SHORTED
75108825             C      SOLENOID VALVE                KSC318569
  MAROTTA VALVE CORP        ML-1        AS501
     N2                        IMPROPER INDICATION
75M08825/1                  SOLENOID VALVE                KSC318578
  MAROTTA VALVE CORP        ML-1        AS501
     N2                        LEAKAGE
75M08825                    SOLENOID VALVE                KSC318604
  1AROTTA VALVE CORP        ML-2        AS502
     N2                        WIRING ERROR
75M08825-2           C      SOLENOID VALVE                KSC318790
  MAROTTA VALVE CORP        ML-2        AS502
     N2                        IMPROPER INDICATION
75M08825             C      SOLENOID VALVE                KSC318862
  MAROTTA VALVE CORP        ML-2        AS502
     N2                        LEAKAGE
END OF PAGE     1
THERE ARE     4 PAGES IN YOUR REPORT
$P*
PG     2 11/09/71  *NRN*  VERB: LIST.   OBJ: P#='75M08825'.
       PART-NUMBER                    PART-NAME          DOCUMENT-NO
       MFG-NAME          LAUNCH-COMPLEX VEHICLE
          FUN-SYS-DESC                   DEFECT-DESC
```

FMSAEG-CORONA,CALIF.   FAILURE RATE DATA PROGRAM   JUNE 1, 1971
TABLE-82-MECHANICAL HYDRAULIC PNEUMATIC PYROTECHNIC MISC. COMPONENT FAILURE MODES BY PERCENT OF TOTAL FAILURES FOR TABLE 0

CROSS INDEX NO.	PARTS/COMPONENTS	NUMBER FAIL-URES	FAILURE MODES BY PERCENT OF TOTAL FAILURES
11625	.VENT-PNEUMATIC-MECHANICAL-ACT-LOX	81	CRACKED, 6% UNKNOWN. 44% LEAKING, 19% INDICATOR DEFECT, 7% SHORTED, 6% OPERATION IMPROP, 6% STICKING, 5% OPERATION NONE, 5% OUT OF TOL, 4% FROZEN, 1% OPERATION INTERMIT, 1% PRESS OUTPT IMPROP, 1% UNKNOWN.
	VALVES,GLOBE		
11634	.CHARGING-SYS-1500-PSIG-3IN	1	100% BENT.
	VALVES,POPPET,ENGINE		
11656	.WITH-PUSHROD-HYDR-TEST-STAND	1	100% LEAKING.
	VALVES,REGULATING,FLUID-PRESSURE		
11659	.	2	50% INOPERATIVE, 50% BROKEN.
11660	.	3	100% LEAKING.
11661	.	6	83% LEAKING, 17% PART FAILURE.
11662	.	64	83% LEAKING, 11% PART FAILURE, 3% BROKEN, 2% INOPERATIVE, 2% STRUCTURAL FAILURE.
11670	.FUEL-DUMP	12	42% MISALIGNED, 42% VIBRATN HI, 8% OPERATION UNSTABLE, 8% RITE'S LOOSE.
11673	.HYDR-TEST-STAND	1	100% LEAKING.
11674	.HYDR-TEST-STAND	1	100% INOPERATIVE.
11675	.HYDR-TEST-STAND	1	100% INOPERATIVE.
11676	.HYDR-TEST-STAND	17	59% LEAKING, 18% PART FAILURE, 18% BROKEN, 6% INOPERATIVE.
11677	.HYDRAULIC-SYSTEM	19	42% REGULATION IMPROP, 32% LEAKING, 11% OPERATION NONE, 5% BYPASSING. 11% UNKNOWN.
11679	.POPPET-3000-3150-PSIG-HYDR-SYS	6	83% LEAKING, 17% PART FAILURE.
	VALVES,RELIEF,PRESSURE/TEMPERATURE		
11683	.FUEL-TANK-20/25PSIA	4	75% CRACKING PRESS HI, 26% OPERATION SLO SLUG.
11687	.HYDR	69	52% OPERATION IMPROP, 28% CONTAMINATE, 12% DAMAGED, 9% LEAKING.
11689	.LOX-31PSIG	1	100% O RING FAILURE.
11690	.LOX-TANK-30PSIA	328	50% DAMAGED, 28% LEAKING, 19% CONTAMINATE, 3% OPERATION IMPROP
11691	.RELIEF-ENGINE-FUEL-SYSTEM	55	35% OPERATION IMPROP, 31% LEAKING, 20% CONTAMINATE, 15% DAM
11703	.	10	50% LEAKING, 20% OPERATION NONE, 10% POSITIONING IMPROP SLO SLUG, 10% OUT OF TOL.
11706	.RELIEF-HYDRAULIC-SYSTEM	16	63% LEAKING, 25% OUT OF TOL, 13% BROKEN.
11708	.RELIEF-PNEUMATIC-OVERRIDE-LOX	24	63% LEAKING, 29% OUT OF TOL, 4% STICK.
11709	.RELIEF-POPPET-SPRING-LOADED-LOX	44	61% LEAKING, 25% OUT OF TOL, 14%
	VALVES,SAFETY-RELIEF		
11721	.AIR-CONDITIONING-SYSTEM	6	67% OUT OF TOL, 17% OPERATIO
	VALVES,SHUTTLE		
11731	.HYD-SYS	4	75% LEAKING, 25% MECH
	VALVES,SOLENOID		
11734	.3-WAY-FLAP-CONTROL-EMERGENCY	7	47% BURNED OUT,
11738	.CABIN-HEATER		
11743	.CABIN-HEATER-28VDC		
11744	.CABIN-HEATER-28VDC		
11746	.ELEC-SYS-HYDR-TEST-STAND		
11750	.GATE-2-WAY-2-POSITION POSITIONINDICATI		
11753	.HYD-4-WAY-DIKE		
11757	.LAUNCH-RELI		

Figure 4-3 Sample FARADA Page

From the above literature,sufficient information, in conjunction with the
designer's own analysis, is available to identify operational effects,

4.4.3 FAILURE MODE TREE

A graphic form is recommended to consolidate and display the information
obtained in the preceding analysis. One such form, a failure mode tree is
shown as Figure 4-4. This form evolved as a variation of fault tree and
failure mode analyses described in reference 34 of Appendix A.

The uppermost branches of the tree describe the operational effect,Go, No-Go,
or Caution ,expected due to the failure modes of the second row. The failure
mechanism identifies the piece part which failed and the specific problem.
The bottom branches list the causes for the identified failure mechanisms.

Note that the failure mode row identifies that information desired to
establish the condition of, in this case, a solenoid valve. That is, if
the valve actuates or deactuates when commanded, in the proper amount of
time, without leakage, the valve could support an operational exercise.
Proper operation of the switch inspires confidence, but would have no effect
upon component operation under the above conditions.

4.5 COMPONENT ACOUSTIC SIGNATURE (SIGNATURE PREDICTION)

4.5.1 GENERAL

Familiarization with the internal operation of a mechanical device
identification of the noise sources, permits construction of a predicted
acoustical signature. Once this predicted signature is established for
component normal operation, modification of the envelope due to various
component failure modes can be evaluated.

4.5.2 NORMAL OPERATION

In order to predict the effect of a malfunction on the acoustic signature of
a device, it is necessary to understand the device dynamics and failure modes.
The first step is to develop an acoustic signature model for normal operation.
Alterations of this normal signature due to the various failure modes can then
be examined.

D4-10

Improper Force Spring (Low)

Broken Turn Fatigue

Sluggish Operation

Mechanical Bind Armature, Stem

Contamination
Corrosion
Seal-to-Stem Cold Weld
Wear
Lack of Lubrication

Caution/ No-Go Depending Upon Severity

Low Driving Force- Armature

Low Input Voltage

Venting to Atmosphere

Internal Leakage- Stem/Seat

Contamination
Corrosion
Wear
Spring Fatigue
Seat Cold Flow

Defective Contacts- Switch (Actuation)

Moisture Intrusion
Fatigue
Arcing

Caution

Erroneous Indication

Mechanical Bind- Plunger (Deactuation)

Contamination
Corrosion

Open, Short, High Z Coil/Wiring

Moisture Intrusion

No-Go

Fails to Actuate

Mechanical Bind-Stem/ Plunger (Slight Movement)

Contamination
Corrosion
Seal-to-Stem Cold Weld
Inadequate Lubrication

Fails to Deactuate

Improper Spring Force (Low)

Fatigue
Broken Turn

Figure 4-4. Solenoid Valve Failure Mode Tree -75M08825-3

D4-11

Taking the above noise generators and ordering their sequence on a time basis, a plot of relative amplitude (envelope) vs. time was derived. This predicted signature is shown in Figure 4-5.

Notes:
1. Background Noise.
2. Flow Noise, Armature/Plunger Contact.
3. Stem/Seat Impact, Plunger/Switch contact.
4. Armature Slap.
5. Ringing.
6. Stabilized Flow.
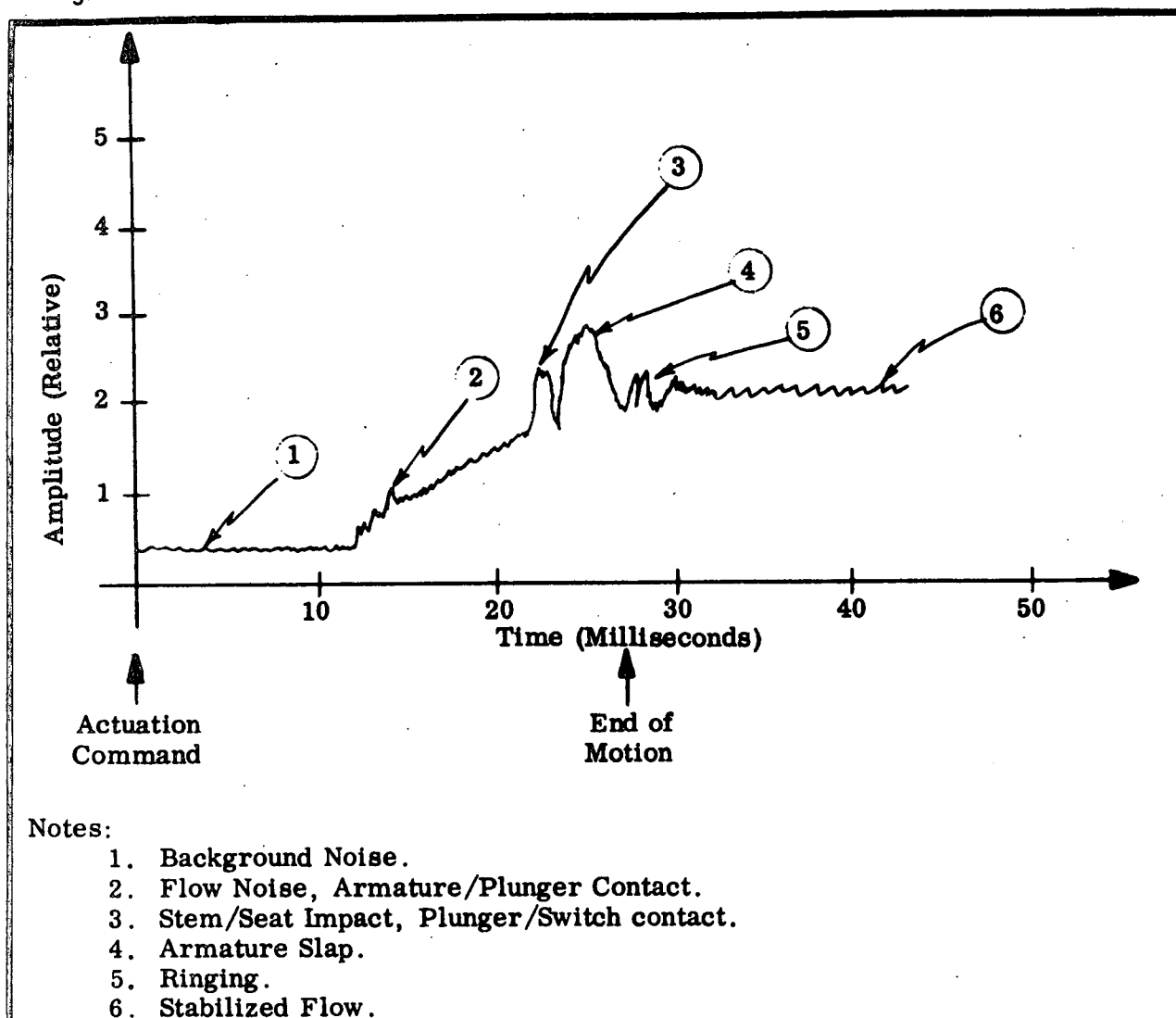
Figure 4- 5. Solenoid Valve Signature Prediction

4.5.3 FAILURE MODE OPERATION

Having established those elements which contribute to the overall acoustic signature for component normal operation, modification of the signature due to identified failure modes can be accomplished.

As an instructive process, it is helpful to tabulate component failure modes and mechanisms (of Figure 4-2, for example) vs. the contributors to the acoustic signature identified in Paragraph 4.5.1. This results in a matrix (Figure 4-6) which assesses the impact of each failure mechanism on each element which contributes to the acoustic signature. With additional familiarity, the effects noted (normal, abnormal, none, etc.) become more definitive.

By modifying the normal acoustic signature prediction (Figure 4-5) per the anticipated changes identified in Figure 4-6, predicted signatures for various failure modes can be constructed. Figure 4-7 shows sample presentations for the solenoid valve.

4.6 SUMMARY

Analysis of component operation, functionally and mathematically, provides a systematic approach to understanding the mechanics of the noise generator, the failure modes, failure mechanisms and the noise producing interactions. This, in turn, permits construction of a predicted signature, for both normal and failure mode operations.

Analysis of the component for normal and failure mode operation is accomplished in order to relate the acoustic test data to the physical events taking place. Identification of the resulting signature characteristics for normal and failure mode operation can then be applied for making component Go, Caution or No-Go decisions. The component analysis also aids in selection of the optimum measurement technique for extracting meaningful acoustic parameters. Thus, it is concluded that the component analysis process is an important step and should be a definite part of methodology employed for implementing SBA.

Figure 4-6

Solenoid Valve Failure Mode/Acoustic Element Matrix

Solenoid Valve
75M08825-3

Elements Contributing to Acoustic Signature

Failure Mode	Failure Mechanism	Slapping of Solenoid Cap (Armature)	Armature/Plunger Contact	Plunger/Switch Contact and Stem Movement	Stem/Nylon Seat Impact	Flow Noise	Ringing of Armature/Plunger/Stem/Valve Body
Normal Operation	N/A	N	N	N	N	N	N
Fails to Actuate	Mechanical Bind-Stem/Plunger (Slight Movement)	0	A, R	0	0	A	A
	Defective Coil Wiring	0	0	0	0	0	0
Fails to Deactuate	Improper Force-Spring (Low)	0	N/A	A	0	A	A
Erroneous Indication	Mechanical Bind-Plunger (Deactuation)	N	N/A	A	N	N	N
	Defective Contacts-Switch (Actuation)	N	N	N	N	N	N
Venting to Atmosphere (1)	Internal Leakage-Stem Seat	N	N	N	N	A	N
Sluggish Operation (2)	Low Driving Force-Armature	A	A	A	A	N (3)	A
	Mechanical Bind-Armature, Stem	A	A	A	A	N (3)	A
	Improper Force-Spring (High)	A	A	A	A	N (3)	A

NOTES:

N — Normal
A — Abnormal
0 — None
R — Reduced Amplitude
I — Incremental Change
N/A — Does Not Apply

(1) Detectable prior to actuation by higher ambient noise level.

(2) Detectable by actuation time.

(3) Abnormal prior to end of stem travel.
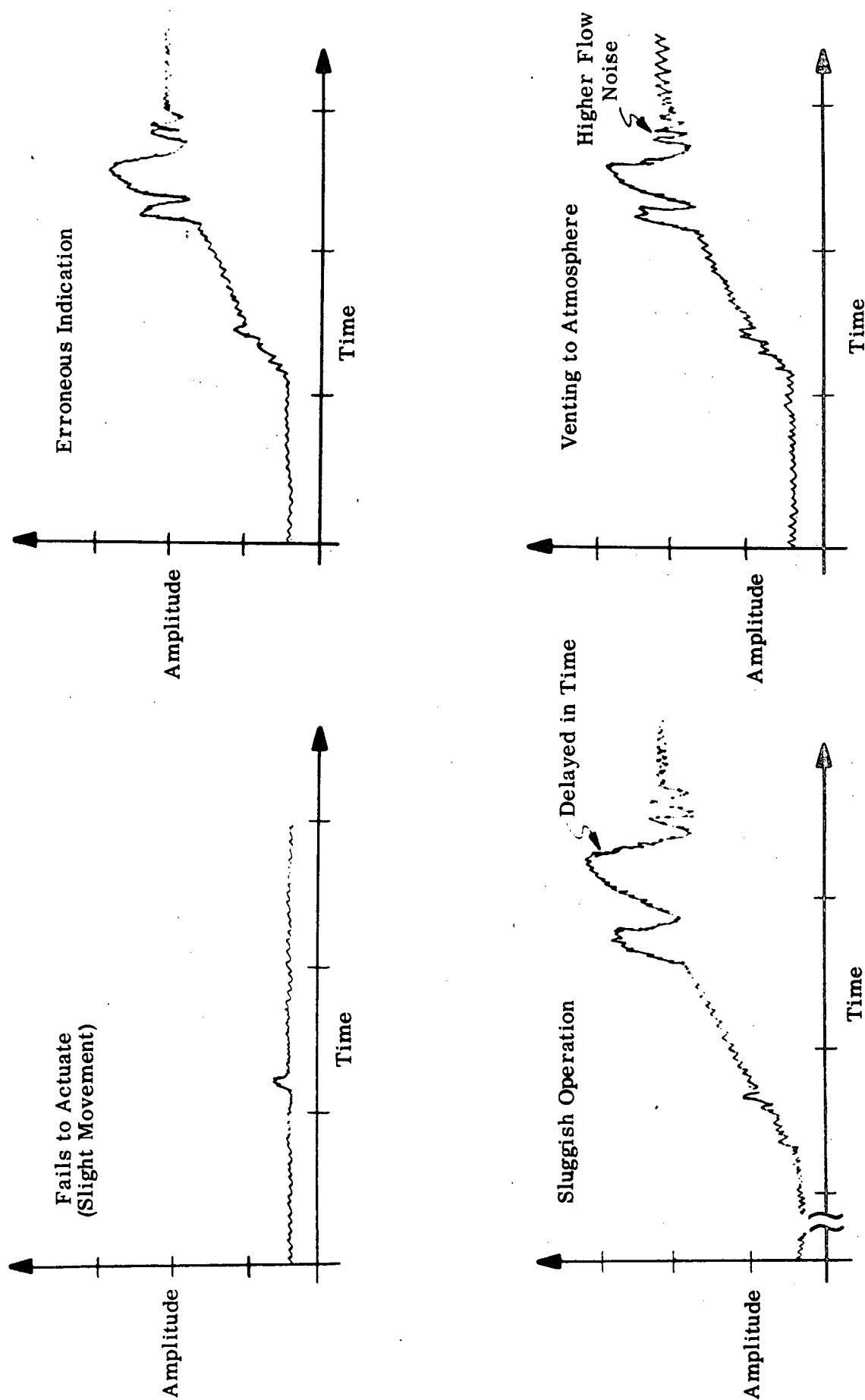
Figure 4-7. Failure Mode Effect Upon Solenoid Valve Signature

CHAPTER 5

THE "MEASUREMENT" SYSTEM

5.1 INTRODUCTION

The factors relative to the selection and use of a SBA measurement system
are discussed in this chapter. The test equipment necessary for Structure
Borne Acoustic implementation can be grouped in three broad categories, Data
Acquisition, Data Processing, and Data Display. This equipment makes up a
standard "Measurement System" with the elements as depicted in Figure 5-1.
For on-line, automatic non-destructive testing, the tape recorder can be
removed from the test loop.
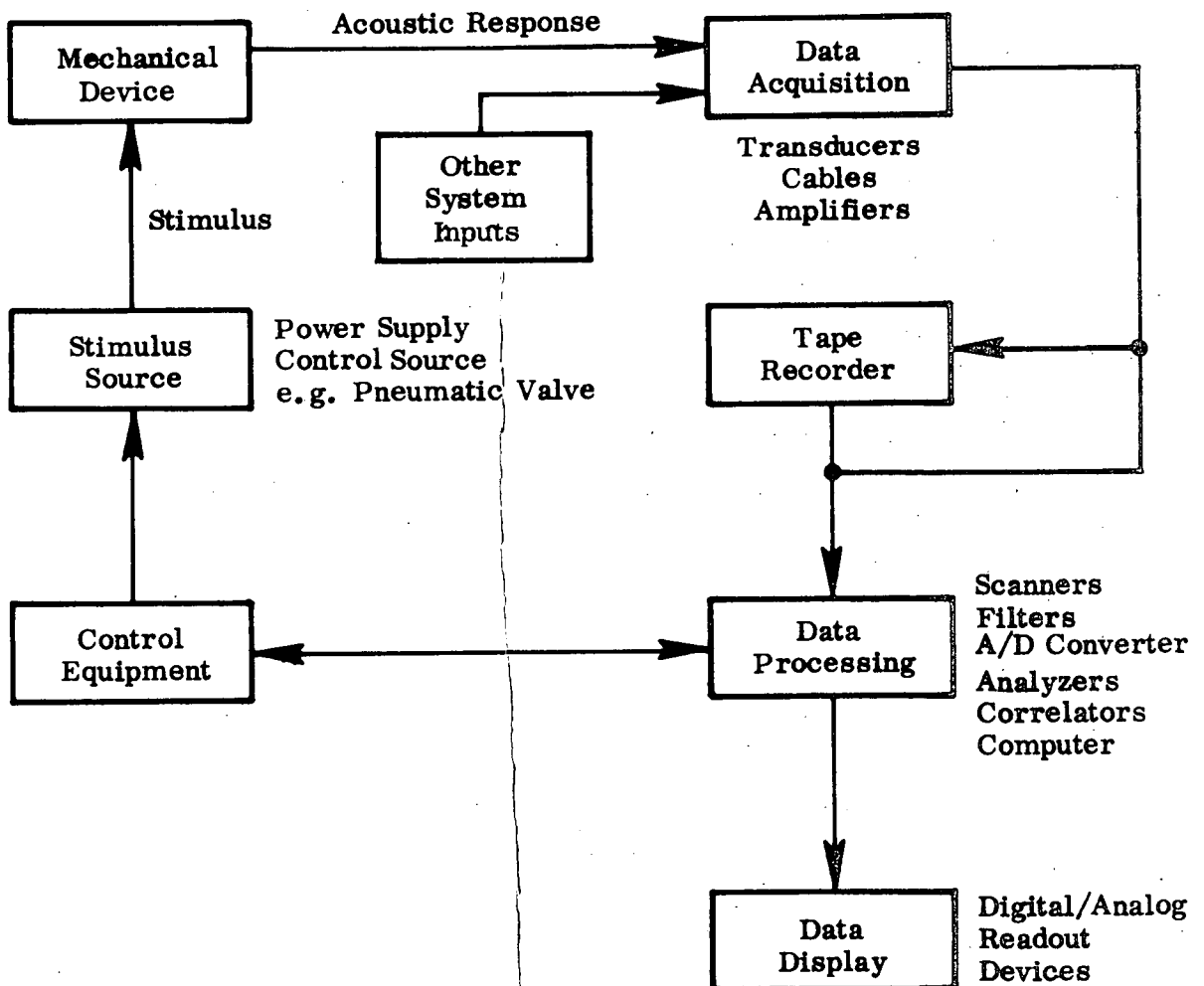
Figure 5-1. Measurement System

5.2 DATA ACQUISITION

5.2.1 TRANSDUCERS

One of the first decision points in the acoustic instrumentation of a mechanical device is the choice of pick-up or acoustic transducers. Structure borne sound is easier to interpret than is radiated sound since it is not subject to the uncertainties of the vibrating surface's radiation impedances and the level of sound variations caused by temperature, air density, etc. Structure borne measurements, however, have their own problem areas, for example, unlike airborne pressure vibrations which are scalar quantities, structure borne acceleration and velocity are direction dependent.

If the full linear frequency range of a pick-up is to be achieved, care must be taken when mounting a vibration pick-up to attach it ridgidly to the object being measured. Resonances in the response curve introduced by poor methods of mounting can be very troublesome when the pick-up is subject to shock excitation leading to error signals, possible overloading of filters and amplifiers, and difficulties with interpretation.

Transducers for the measurement of vibration and pressure employing electromagnetic, electrodynamic, capacitive, piezoelectric or strain gauge principles of operation are commercially available. Of these, the most widely used in recent years is the piezoelectric accelerometer, largely by virtue of the fact that it is self-generating, is small in size and weight, can be designed to be free of resonances over a wide frequency range, has good stability, low sensitivity to strain, temperature variations, airborne sound and magnetic fields, a large dynamic range, low cost, and is not easily damaged. It is this type of transducer recommended for SBA implementation.

Choice of the proper transducer and its correct usage are critical to the successful implementation of SBA. These factors are discussed at length in Addendum B. The Endevco Corporation Instruction Manual for Piezoelectric Accelerometers (#101) is an excellent reference concering this type of transducer and the majority of transducer data presented herein is excerpted from this manual (courtesy Endevco Corporation).

D5-2

5.2.2 MOUNTING

For an accelerometer to generate accurate and useful data, it must be properly coupled to the equipment under investigation. The method of attachment must not introduce any distortion. This requires that the accelerometer mounting be rigid over the frequency range of interest. In practice, many mounting methods are suitable for a wide variety of applications and depend on the practical requirements of the test system.

5.2.2.1 Standard Stud Mounting

When possible, the best method is to mount the accelerometer with a stud so that the entire base of the accelerometer is in good contact with the test object. Care should be taken to ensure a flush mating with a smooth, flat surface. The mounting hole must be at a right angle to the surface. Ordinary machine screws are to be avoided since without a flange or shoulder, it is possible to "bottom" the screw in the accelerometer, thereby changing its dynamic response and, in some cases, causing damage to the unit.

5.2.2.2 Insulated Mounting Studs

Insulated mounting studs provide isolation of the accelerometer from electrical ground, and are particularly useful in preventing ground loops.

5.2.2.3 Cementing Studs

A series of cementing studs is available which permits accelerometer attachment to surfaces that cannot be drilled and tapped to accept threaded studs. Use of these studs rather than cementing the transducer directly to the test specimen will prevent contaminating accelerometer mounting threads with adhesive. Removal of the accelerometer will also be facilitated. Adhesives should not be scraped or sanded off from accelerometer since a rough mounting surface can cause poor frequency response and/or an increase in transverse sensitivity.

Commonly used cements include Eastman 910 (Tennessee Eastman Company, Kingsport, Tennessee), EC-1294 (Minnesota Mining & Manufacturing Company, Detroit, Michigan), and Epon 828 (Shell Chemical Corporation, New York). Dental cements, such as Grip (L. D. Caulk Company, Milford, Delaware) are useful when the mounting surface is irregular or when the transducer will be subjected to high humidity or immersion. Efficiency of this technique depends entirely on the adhesive used, thorough evaluation is recommended for the individual application. Remove Eastman 910 Cement with N-Dimenthlyl-formamide.

5.2.2.4 Application Notes

Poor accelerometer mounting surfaces will result in unreliable data. It is recommended that the mounting surfaces and tapped holes conform to the following specifications. These are considered to be easily achieved by following good machine shop practices:

Surface Flatness:	0.0003" TIR
Surface Roughness:	32
Perpendicularity of Hole:	$\pm$ 6 minutes
Tap Class	2

For all studs, the use of a drop of light oil between the mating surfaces is recommended when frequencies are above 5000 Hz or shock pulse durations are short. If no oil is used, the mechanical connection to the structure may not be rigid enough, and the resonant frequency of the mounted accelerometer may be reduced by 5 to 10 kHz. This means that the rise in response at 10 kHz for an accelerometer with a nominal 35 kHz resonance can be cut approximately in half through the use of oil. This represents an improvement of 5% in the frequency response at 10 kHz. No evidence of an improvement due to the use of oil has been noted below 5 kHz.

5.2.2.5 Effects of Mounting

In some instances, the very act of performing a measurement affects the system being measured and, thus, changes the nature of the data obtained. With piezoelectric accelerometers, this may occur for two reasons: (1) the fixture required to couple the accelerometer to a somewhat flexible structure may introduce local stiffening which changes structural response, and (2) the added mass of the fixture and/or transducer may change the system characteristics. Effects due to either cause can be reduced or eliminated by choosing as small and light an accelerometer as possible. Microminiature Accelerometers weigh only a few grams and are small enough to approach point loading in many cases.

For a simple spring-mass system, the effect of added mass is to reduce the system's resonant frequency. The amount of reduction can be calculated from the following equation:

$$\Delta f_n = f_n \left(1 - \sqrt{\frac{m}{m_a + m}} \right)$$

Where

f_n = system resonant frequency

Δf_n = change in resonant frequency

m = system mass

m_a = added mass

A more general approach to loading effects is based on mechanical impedance considerations. Since piezoelectric accelerometers have nearly zero internal damping, the apparent weight (and mechanical impedance) of the accelerometer is constant at all frequencies from zero up to approximately 0.9 of its resonant frequency and must be equal in value to its physical weight. Within this range, the effect of the accelerometer on the structure motion is given by:

$$a_r = a_o \left(\frac{m_s}{m_s + w_t} \right)$$

Where

a_r = resultant acceleration

a_o = acceleration without accelerometer attached

w_t = weight of accelerometer

m_s = apparent weight of structure

This statement of <u>Norton's Theorem</u> indicates that mounting an accelerometer will change the motion of a structure if the structure's apparent weight is not large compared to the total weight of the accelerometer. For most applications, the effect of the accelerometer on structure motion is not significant and the apparent weight of the accelerometer may be ignored.

5.2.3 CABLES

The cable which connects a transducer to its matching electronics is an important part of the overall measurement system. It must transmit the transducer signal to the associated signal conditioning equipment without distortion or introduction of noise.

Noise can be introduced either by pickup from nearby electrical (or magnetic) fields or by internal generation due to cable motion. Since piezoelectric accelerometers are high impedance devices, the pickup problem could be quite severe. For this reason, coaxial cables are required. Generated cable noise is eliminated by a special "treatment" which prevents triboelectric effect, the primary cause of cable noise. Triboelectric effect can be represented as shown in Figure 5-2.
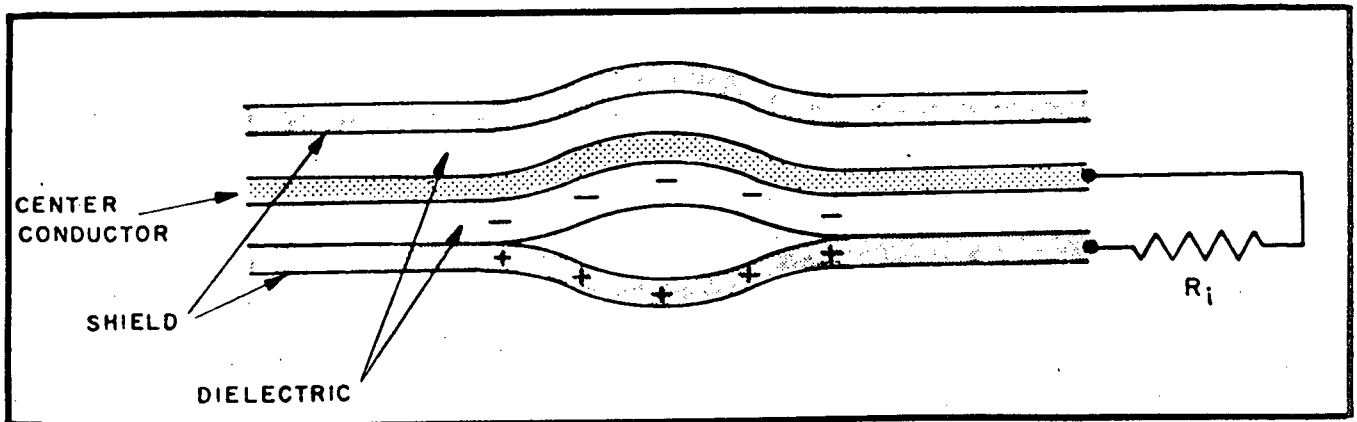
Figure 5-2

Triboelectric Effect in Coaxial Cables

When coaxial cable is flexed, squeezed, or in some other way mechanically distorted, the shield and dielectric may separate, resulting in the generation of some triboelectric charges. The charges on the dielectric are trapped by the low conductivity of the dielectric material. The charges on the shield, however, are mobile and neutralize by flowing from the inner conductor through the terminating impedance, generally the input stage of the coupling amplifier. This momentary current flow produces a signal pulse at the amplifier input. When the cable distortion is relieved, dielectric and shield are joined together and the formerly trapped electrons now flow into the shield, resulting in a second pulse of opposite polarity. (Untreated cables can generate noise of greater amplitude than the output of the accelerometer).

Noise-treated cables have a conductive coating applied to the surface of the dielectric which allows redistribution of any local charges during mechanical separation from the shield.

In addition to good noise characteristics, the cable must not affect transducer or test specimen characteristics. Good transducer cables are as small, light and flexible as possible, considering their specific intended application. Stiff or massive cables can severely distort normal response, particularly with light, flexible specimens.

Although fairly rugged, cables should be handled with care - they can be damaged if misused. They should not be stepped on, kinked, knotted, etc. When attaching (and detaching) cables, care must be taken not to bend the center pin of the cable connector, which is relatively susceptible during these operations. Cable connectors should be securely tightened - careful use of pliers may be made.

When possible, the cable should be tied down within 2 to 3 inches of the transducer connection. Long unsupported length of cable may load the test specimen and lead to cable damage. Good housekeeping should be observed - excess cable should be neatly coiled and tied down. In humid environments, it is good practice to provide a drip loop at the accelerometer. It is also advisable to seal the cable connector to prevent moisture from entering the cable assembly. If the connector insulation has become damp (or otherwise contaminated), it should be wiped dry with alcohol or a dry, clean cloth.

At very high sustained vibration levels, the energy present is sufficiently high that considerable heat is generated in the accelerometer cable. (Several minutes at 3000g and 6 kHz heats the cable bend relief enough that the accelerometer is too hot to touch). For this reason, high temperature cable should be used in applications where high frequency continuous sinusodial vibration exceeding 100g will be encountered.

5.2.4 ELECTRONIC PREAMPLIFIERS

Piezoelectric accelerometers can be operated into either charge sensing or voltage sensing amplifiers. Both types of equipment are available in a wide variety of configurations.

Charge amplifiers sense the actual charge developed in the crystal. They can operate at much lower input impedances than voltage equipment; system low frequency response is not a function of RC time constant and is determined only by the amplifier frequency response characteristic. Lower input impedance reduces problems with noise pickup and with connector contamination (even a 10 MΩ leakage path across the insulation results in reduced voltage system performance). Since charge is the parameter sensed, system sensitivity is unaffected by the length of cable between accelerometer and amplifier, or by changes in cable length. This means that an accelerometer-charge amplifier system can be calibrated in the Lab with any convenient length of cable and the calibration will still be valie when installed in, say, a missile in which the cable is already installed in a pre-wired harness.

A voltage amplifier may provide gain or may be simply a cathode follower, with unity gain. The high input impedance provides a matched termination for the high internal source impedance of the accelerometer. The high input impedance also permits long RC time constants for good low frequency response. System sensitivity will be reduced as longer interconnecting cables are used between accelerometer and amplifier.

5.2.5 SYSTEMS GROUNDING

One important system consideration is prevention of ground loops. This problem can occur when the common connection (or signal return) in the system is grounded at more than one point (Figure 5-3). Differences in earth potential up to several volts may exist between various grounding points. This potential difference can produce circulating ground currents that introduce noise in the measuring system.
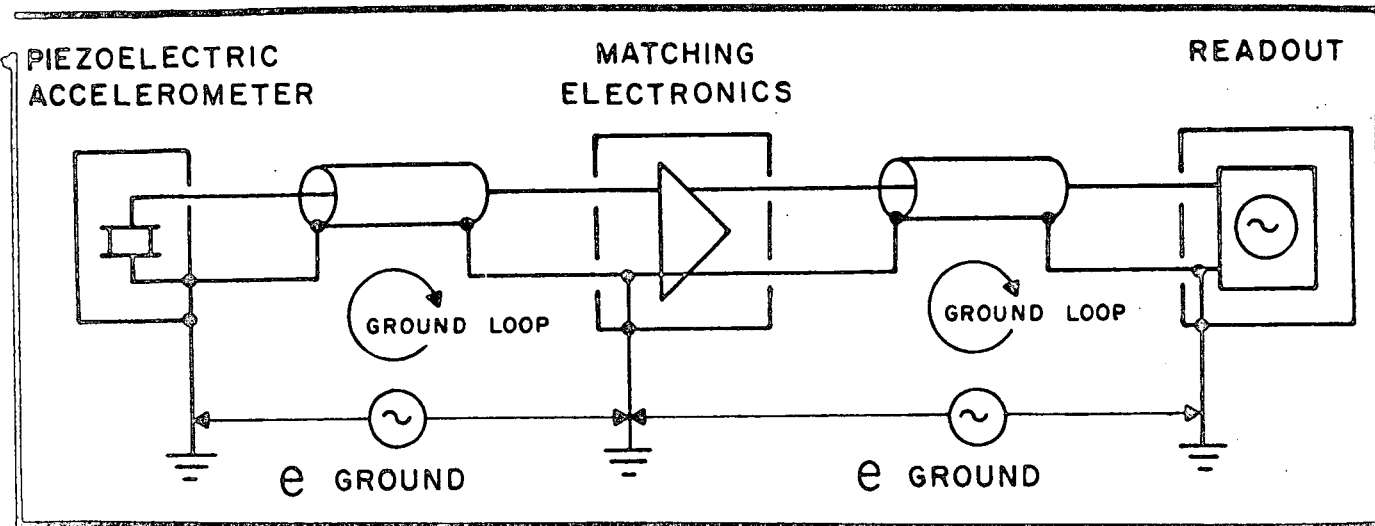
FIGURE 5-3

Ground Loops in Typical Piezoelectric Accelerometer
Installation

The only method of preventing ground loops is to ensure that the entire system
is grounded at a single point. In general, the most satisfactory system
ground point is at the readout input. (When several channels of data are
being simultaneously fed to the same recorder, it is mandatory). This requires
that both accelerometer and amplifier be insulated from ground.

One technique of accelerometer isolation involves electrically insulating the
sensing element from the transducer housing to provide a floating output.
With this approach, the accelerometer case is at ground potential, but is not
connected to the "low side" of the signal. This method, however, has a serious
drawback. Capacitive coupling between case and transducer element permits
coupling of AC noise directly into the (high impedance) transducer.

A much better and simpler technique is to electrically isolate a normal
accelerometer from the structure to which it is mounted. Using this method,
while the accelerometer is removed from earth ground, the transducer element
is still shielded by the transducer case which is at circuit ground potential.
This grounded shield is required to prevent capacitive coupling problems.
They provide good transmissibility and insulation over a wide range of frequencies
and acceleration levels.

D5-10

When using cementing techniques, isolation can be ensured by "sandwiching" a rigid insulating material (such as Mycalex) between the structure and accelerometer (or base of cementing stud). Dental cements alone are also quite satisfactory insulators.

Matching electronics in which the case is tied to circuit ground can be satisfactorily isolated by wrapping with insulating material (electrical tape, etc.), or by simply placing on paper or cardboard. (In severe environments, the amplifier can be wrapped with sponge rubber).

If amplifier output cables are unjacketed, care must be taken that any exposed shields or connectors do not become inadvertently grounded ahead of the recorder input.

The best method of determining accelerometer system performance is by true dynamic calibration of the entire operating system. In the laboratory, such calibration can be readily performed with good accuracy using electrodynamic shakers. In field testing, however, shaker calibration is usually impractical. Instead, a voltage substitution technique is frequently employed. This procedure, also called "calibration simulation," does not calibrate the entire system. Instead, a simulated transducer output is provided which (1) checks system continuity, (2) permits proper setting of system gains, (3) evaluates electrical performance of preamplifiers, signal conditioning equipment, readout and data storage devices under conditions which closely simulate the actual measurement situation.

The usual method is to insert a voltage signal in series with the ground side of the transducer cable. This may be accomplished by breaking the ground side and inserting a calibration resistor, across which a predetermined calibrating signal is applied.

5.3 DATA PROCESSING

Once the acoustic data has been acquired in a useable form by the data acquisition subsystem, it must then be manipulated, reduced, analyzed, correlated, and transmitted to appropriate display devices. The equipment necessary to complete

this action includes electronic assembly scanners, filters, analyzers, meters, correlators, and computers. All of which are classified as Data Processing hardware and will be discussed in this section.

5.3.1 MAGNETIC TAPE RECORDERS

The acoustic data may be processed "live," i.e., without tape recording, or the signals may be taped for subsequent analysis. In most applications, some analysis will be necessary before readiness assessment limits can be established, or "trend" baselines established, and the system can operate fully automatic. Therefore, the magnetic tape recorder is required in the implementation of SBA.

There are three important factors which contribute to making satisfactory tape recordings. These include proper documentation, high-fidelity recording, and suitable calibration.

A tape recording has value only when the information recorded can be meaningfully retrieved. This requires complete documetation of all the pertinent conditions under which the recording is made. The data includes the reel identification number, the model of the recorder used, the tape speed, the date of the recording, and a description of the subject of the recording. It is a good practice to include a voice commentary on each tape. The redundancy is valuable in case the data sheets are ever lost, and the commentary is often an aid in identifying important events during tape playback. Figure 5-4 and 5-5 are examples of acceptable log formats.

Standards for instrumentation recordings have been established by the Inter-Range Instrumentation Group (IRIG). Compatibility and exchange of recorded data between various magnetic recording systems demands adherence to such standardization. "IRIG Telemetry Standards," Document No. 106-69, dated February 1969, describes these standards.

Three categories of instrumentation recorders have been established by IRIG: low-band, intermediate-band, and wide-band. These categories provide bandwidths, respectively, of 100 kHz, 500 kHz, and 1.5 MHz.

REEL NUMBER: GSFC 6A
TAPE RECORDER: CEC PR 3300
TAPE SPEED, IPS: 60
DATE: 8-21-68
TEST DESCRIPTION: *Test of components with introduced defects at NTTF.*

x-axis hydraulics — *Endevco 2895 system* — *Anvre 851B decade ampl. (optional)* — *calibrated attenuator* — *Tape recorder*

IRIG CH.	1	2	3	4	5	6	7
FM FREQ.	54 KHz		54		54		54
DIR. REC.							

IRIG CH.	8	9	10	11	12	13	14
FM FREQ.		54					
DIR. REC.				X		X	

IRIG CHANNEL	PARAMETER
1	*Servo pump roller bearing vibration*
2	—
3	*Servo pump discharge port vibration*
4	—
5	*Replenishing pump vibration*
6	—
7	*Control pump vibration*
8	—
9	*Voice commentary*
10	—
11	*Pressure relief valve vibration*
12	—
13	*1/rev trigger signal*
14	—

Figure 5-4   Sample Tape Recorder Parameter Log

REEL NUMBER: GSFC 6A

RECORDING   COUNTER (REVOLUTIONS)   TEST DESCRIPTION

1	0 - 206	Calibration 100mv RMS at 60Hz, ch. 1, 3, 5, 7 Calibration 0.5V p-p sq. wave ch. 11 het attenuation ea. channel (in sequence) 0, -10, 0, 0, 0, -10, -10 DB
2	206 - 690	Run with servo pump yoke centered het attenuation 0, -10, 0, 0, 0, -10, -10 DB
3	702 - 1178	Run test at 1 deg./sec. het attenuation 0, -10, 0, 0, 0, -10, -10 DB
4	1178 - 1648	Run test at 2 deg./sec. het attenuation 0, -10, 0, 0, 0, -10, -10 DB
5	1648 - 1980	Run test at 3 deg./sec het attenuation 0, -4, 0, 0, 0, -10, -10 DB
6	1980 - 2245	Run test at 4 deg./sec. het attenuation 0, 2, 0, 0, 0, -10, -10 DB
7	2245 - 2665	Run test at 3 deg./sec. het attenuation 0, -4, 0, 0, 0, -10, -10 DB
8		
9		
10		

Figure 5-5   Sample Tape Recorder Test Log

For SBA implementation, only the low band recorder is needed. Its standardized tape speeds are 1-7/8, 3-3/4, 7-1/2, 15, 30, & 60 inches per second.

There are two recording methods employed in today's recorders: Direct Recording, and Frequency Modulation Recordings. Direct Recording provides the widest bandwidth availability and is less expensive than FM recording. While this type of recorder may be used, its design is subject to amplitude instability - approximately 10% error near upper bandwidth limits and momentary signal decreases of over 50%, known as dropouts. FM recording does not have the high frequency bandwidth response of direct recording. However, as previously stated, in SBA applications, low-band bandwidth is adequate. FM recording significantly improves the signal amplitude stability. The signal reproduction accuracy of FM recording is also on the order of 1%, vs. 5% for the direct recording process. Therefore, the FM recorder is recommended for achieving the fidelity needed for mechanical device SBA.

Any of a number of conveniently available recorders are adequate for SBA. A representative list of magnetic tape recorder manufacturers is included in Addendum H. Addendum F illustrates a few representative manufacturers specification sheets.

One of the SBA tests must be a calibration. With this, it will always be possible to relate the retrieved signals to absolute vibration levels. The value of being able to measure absolute levels may not be immediately apparent; in fact, it may not be necessary. On the other hand, it is not always possible to forsee all the future uses of recorded data. A calibration can be ignored, but it cannot be added with confidence at a later date.

Making a recording which is a faithful reproduction of the original signal has two aspects. First, the recorder and its mode of operation must have sufficient signal components. Second, the signal must be recorded so as to make best use of the recorder's dynamic range. If the signal is too strong, it will overload the recorder and cause distortion, while if it is too weak, it will be obscured by the recorder's inherent self-noise. It is common for magnetic tape recorders to be set up to accept a 1-volt RMS sine wave with

some small (on the order of 3%) distortion. The maximum excursion of such a signal is $\pm$ 2 volts.. If nonsinusoidal signals are recorded on this machine, their amplitude should be adjusted so that their maximum excursions approximate the range. This ensures that both distortion and noise will have minimal effects.

5.3.2 DATA REDUCTION

When choosing the type of SBA data reduction or signal processing, the aim is to select processing which can extract from the acoustic signals only that information which is useful in providing readiness assessment.

The main problems are to obtain a satisfactory ratio of wanted-to-unwanted signals and a sufficient degree of precision in the signal processing.

These factors and the nature of the signals to be processed whether periodic, narrow, or wide-band random, impulsive, or transient will largely determine the data reduction technique to be employed. The available data reduction techniques and resulting discriminants are itemized in Figure 5-6.
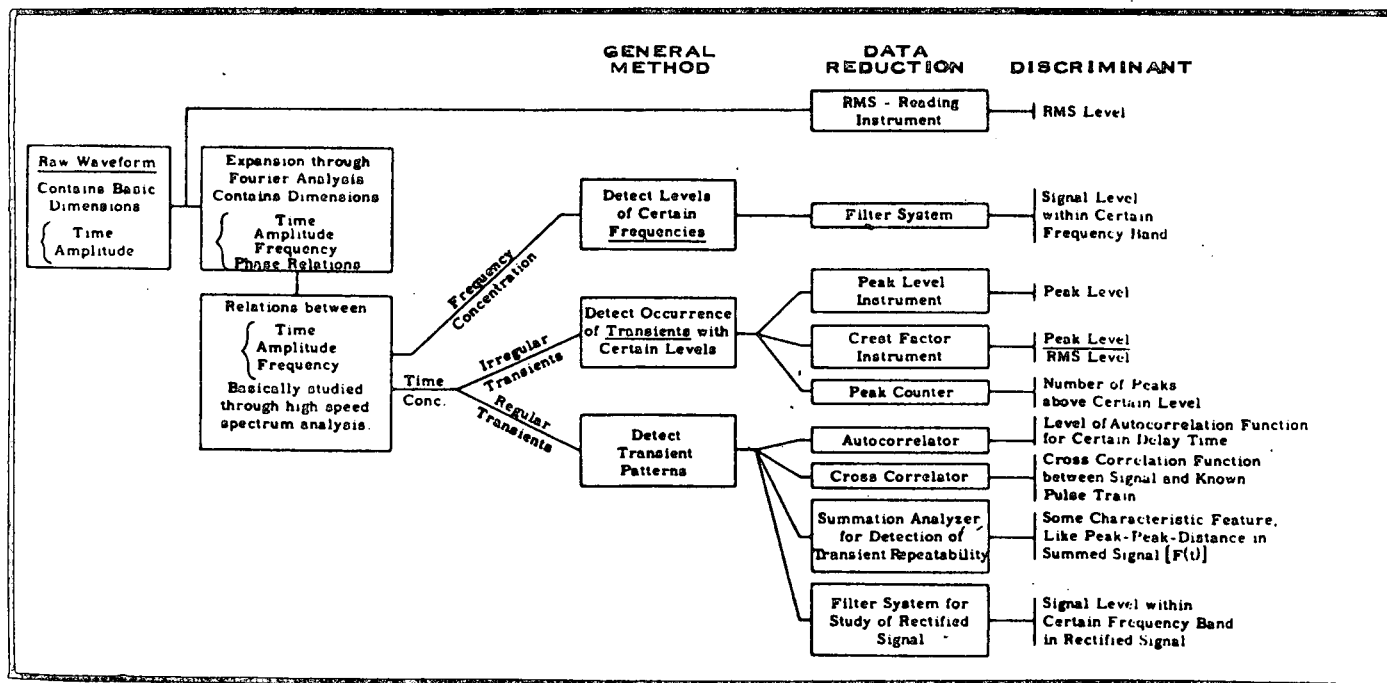
Figure 5-6   Block Diagram of Data Reduction/Processing Techniques

5.3.3 OVERALL MEASUREMENTS*

The simplest physical measure of an acoustic signal is its overall level and this is normally expressed by its overall rms (root-mean-square) value as given by:

$$A_{rms} = \sqrt{\lim_{T \to \infty} \frac{1}{T} \int_0^T X^2(t)\,dt}$$

where X is the instantaneous amplitude of the signal.

Thus, to measure the true rms value necessitates a correct squaring of the waveform and "averaging" over a period T sufficiently long to be equivalent to infinity.

In the case of periodic waveforms, this condition is met by integrating over the fundamental period, but in practice with traditional rms detectors the limitation is imposed by the "time constant" T_0 of the averaging circuit. Thus, even with signals that are periodic and approximate to sine waves, the time constant T_0 of the rms detector circuit must not be less than about $2/f$ seconds (where f = frequency of signal), if the ripple uncertainty is to be less than 6% (approximately 0.5 db).

When the signal to be processed is random in character, then for a finite 'averaging time T' the observed rms value will fluctuate, the magnitude of these fluctuations increasing as the frequency bandwidth of the signals decrease. The standard deviation of the fluctuations in the observed rms value (as a percentage of the correct, infinite averaging time rms value) is given by -

$$\int (\%) = \frac{50}{\sqrt{BT}}$$

where B = Bandwidth of random signal in Hz.

T = KT_0 = Effective Averaging time of rms detector in seconds.

(K = 2 for simple RC averaging filter)

*Paragraph 5.3.3, 5.3.4, and portions of Paragraph 5.3.6 provided through the courtesy of Dr. C. M. Brownsey, Section Head of the Acoustics, Vibration, and N.D.E. Section of the Central Electricity Research Laboratories (Leatherhead, Surrey, England), and the Institution of Mechanical Engineers (Westminster, London).

Thus if δ is not to exceed 6% (approximately 0.5db) then BT must not be less than 72 (i.e., BT_0 not less than 36).

The determination of the rms value of a signal has obvious advantages when considering signal power and is equally significant when dealing with pure tone or random signals.

The 'peak' value of the amplitude of a signal is sometimes used as an overall measure but such a measurement has no direct meaning when applied to random signals where the instantaneous amplitude may (theoretically), become infinite. Thus the quantity indicated is entirely dependent on circuit time constants and the dynamic range of the measuring equipment. It should also be remember- ed that so-called peak values are affected by phase shifts in the measurement circuits.

In general, data processing equipment should be capable of handling signals having a crest factor (peak/rms ratio), of up to 5 while retaining a dynamic range of at least 50 db at any setting of the controls.

Where an overall measurement does meet the requirements for a satisfactory diagnostic test but the mean levels are subject to statistical variations (e.g., in production testing), then a reliable estimate of a mean level and the variability about the mean may be found by employing a Statistical Dis- tribution Analyzer. Subsequent processing to a digital readout is par- ticularly useful in such cases.

Although a simple measure of the overall level of an acoustic signal is rarely adequate even for normal noise work, measurements of overall 'weighted' sound pressure level is sometimes useful. A more detailed frequency analysis of the signals is likely to prove more helpful.

5.3.4   SPECTRUM ANALYZERS

A generalized signal consists of some combination of discrete-frequency spectral components and random noise. The discrete-frequency components can be separated by means of frequency filtering, provided that the energy of the desired signal exceeds the sum of all other signals, as measured within the passband of the filter. By decreasing the filter bandwidth, the noise is

D5-18

increasingly discriminated against, while acceptance of sinusoidal signals within the passband is unchanged. While one might at first conclude that this process could be continued indefinitely so that weaker and weaker sinusoids could be detected, there are practical limitations in building such an analyzer.

As the filter becomes more selective, its tuning becomes more critical, and finally a point is reached when it is often found that the supposedly stable sinusoid actually is wandering somewhat in frequency. Its bandwidth is not really zero, but finite, and an excessively narrow filter will actually increase measurement errors. There are other practical problems having to do with the permissable tuning rate of the filter (which is an important consideration when a tunable filter is to be scanned over a range of frequencies), filter stability, and the shape of the filter passband. Despite these problems, the technique is well suited to the separation or extraction of particular components of complex signals within the limitations described.

A periodic or random signal may be processed to determine how the various frequency components which together make up the waveform are distributed throughout the frequency range of interest. In selecting suitable equipment, the first considerations will be:

    (1) the bandwidth to be employed.

    (2) the method to be used for scanning the frequency range of interest. Frequency analyzers fall into two classes according to the type of bandwidth employed, namely constant percentage bandwidth or constant bandwidth analyzers. Such analyzers may be further subdivided as either broadband or narrow band.

Constant percentage bandwidth analyzers having bandwidths of an octave or one-third of an octave are widely used for acoustic work as the audible frequency range from about 20Hz - 12000Hz may be conveniently covered by nine contiguous octave filters or twenty-seven one-third octave filters.

Such broadband analyses are often adequate for diagnostic purposes, but where the determination of a frequency spectrum in great detail is required, then a narrow constant bandwidth analyser will be required.

An analyzer having a constant bandwidth in cycles per second will impose more exacting requirements on the attenuation required outside the pass band than will a constant percentage bandwidth analyser, and if these requirements are not met, will give misleading results usually at the high frequency end of the spectrum. With such an analyser, manual searching for components can become very difficult and unless the frequency of the components is sufficiently stable, readings are often impossible.

For the "optimum" conditions, the scanning rate and the rms detector effective averaging times remain constant for any given constant bandwidth analysis whereas the scanning rate is proportional to f^2 and the effective averaging times inversely proportional to f for any given constant percentage bandwidth analysis.

Where detailed examination of the resonance peaks in a random signal is necessary, then constant bandwidth analysis is required, but the frequency range of interest must be restricted to give acceptable processing times. As a general guide, the filter bandwidth selected should be not more than one quarter of the bandwidth of the narrowest peaks in the spectrum to be analyzed. The times indicated in Table 5-1 also show the general unsuitability of swept filter techniques for rapid analysis.

The use of a number of paralleled contiguous fixed filters with the filter outputs connected successively to a detector, reduces the possibility of shock excitation and filter transients, but the rms detector time constant is a compromise resulting in degradation of accuracy at the low frequency end of the spectrum.

This difficulty can be overcome by providing each filter with its own rms detector having a time constant T_0 appropriate to the frequency range involved (e.g., varying from 20 seconds at the low frequency end to 20 milliseconds at the high frequency end of the spectrum). By scanning at the output of the detectors, scanning rates are no longer determined by considerations of detector time constants, and analyses over a wide frequency range can be accomplished in a few milliseconds. This is the principle employed in the recently developed 'Real-time' analyzers.

The increased speed of analysis and constant updating of information which characterize 'Real-time' analyzers, have necessitated the introduction of digital readout to take full advantage of the much reduced processing time. Digital techniques have also been applied at the detector stage to ensure accurate well defined 'time slices' and true rms determination.

Real time spectral analyzers are also capable of analyzing impulsive and transient signals whereas the more traditional methods would require that the signal to be analyzed be available as a closed-loop magnetic recording. Addendum E contains a representative listing of spectral analyzer manufacturers and Addendum F itemizes several representative analyzers that are suitable for SBA type application. A more detailed discussion of Frequency Analyzers by I. D. Mcleod, G. Halliwell, and J. G. Hale of the United Kingdom Atomic Energy authority is presented in Addendum G.

Frequent reference has been made to the use of filters and scanners as an integral part of the spectral analysis system. Manual scanning of the frequency range of interest can also be very time-consuming and an automatic scan at the maximum possible rate without degrading the measurement accuracy required, is a distinct improvement.

Automatic scanning can be accomplished by:
  (a) Sweeping the frequency range of interest by a filter of continuously changing frequency.
  (b) Applying the signal to the appropriate number of contiguous fixed filters, the inputs of which are paralleled, the filter outputs being connected in succession to an rms detector.

(c) As (b) except provide each filter output with its own rms detector and scan the detector outputs.

A brief consideration of the scanning times associated with these methods serves to highlight the disadvantages of methods (a) and (b).

It has already been pointed out that when determining the rms value of a signal subject to random amplitude fluctuations, the effective averaging time of the rms detector should not be less than $\frac{72}{B}$ seconds* if the standard error is not to exceed 0.5 db. This relationship, for various bandwidths is shown in Figure 5-1.

When using a 'swept filter' technique it is also usual to ensure that the bandwidth swept during the 'effective averaging time' of the rms detector does not exceed the filter bandwidth.

If the above requirements are to be met, then the minimum scan times for various filter bandwidths and frequency ranges are as indicated in Table 5-1.

| Frequency range of interest (Hz) | Approx. Minimum Scan times (seconds) | | | | | |
| | Constant % Bandwidth | | | Constant Bandwidth | | |
	Octave	3rd Octave	5%	100 Hz	25Hz	5Hz
20 - 1,000	7	67	1,400	7	112	2,800
200 - 10,000	0.7	6.7	140	70	1120	28,000
20 - 10,000	7.2	69	1,440	72	1140	28,500

TABLE 5-1.

In this SBA handbook edition, no further discussion of these more common elements of the SBA system will be included. Representative examples of this hardware, however, are shown in Addendum F.

*For discrete frequencies, the limitation could well be the filter response time of ^{1}/B seconds.

The final choice of SBA scanners and filters design will be a function of the number and complexity of mechanical components instrumented, the level of signal processing required, and the rate and frequency of mechanical system updating required.

5.3.5 SUMMATION ANALYZERS

If an acoustic signal repeats itself in a cylical manner, a powerful tool called summation analysis can be used to extract it from other signals which are non-periodic or of an unrelated periodicity (noise). Since the repitition rate of the wanted signal is known (from the one/rev trigger), it can be summed on itself as shown diagramatically in Figure 5-7 to develop the function F (τ):

$$F(\tau) = \sum_{n=1}^{N} f\,|\,[\tau + (n - 1)\, T_s\,]\,|$$

WHERE N IS THE NUMBER OF SUMMATIONS.

T_s IS THE PERIOD OF THE REPETITIVE FUNCTION.
T IS THE PERIOD OF SCAN OF THE DEVICE WHICH PERFORMS THE SUMMATION.
τ RELATES TO THE RATE AT WHICH THE SUMMED SIGNAL IS READ OUT; THIS REQUIRES .SECONDS FOR A SIGNAL REPRESENTING T SECONDS IN REAL TIME.
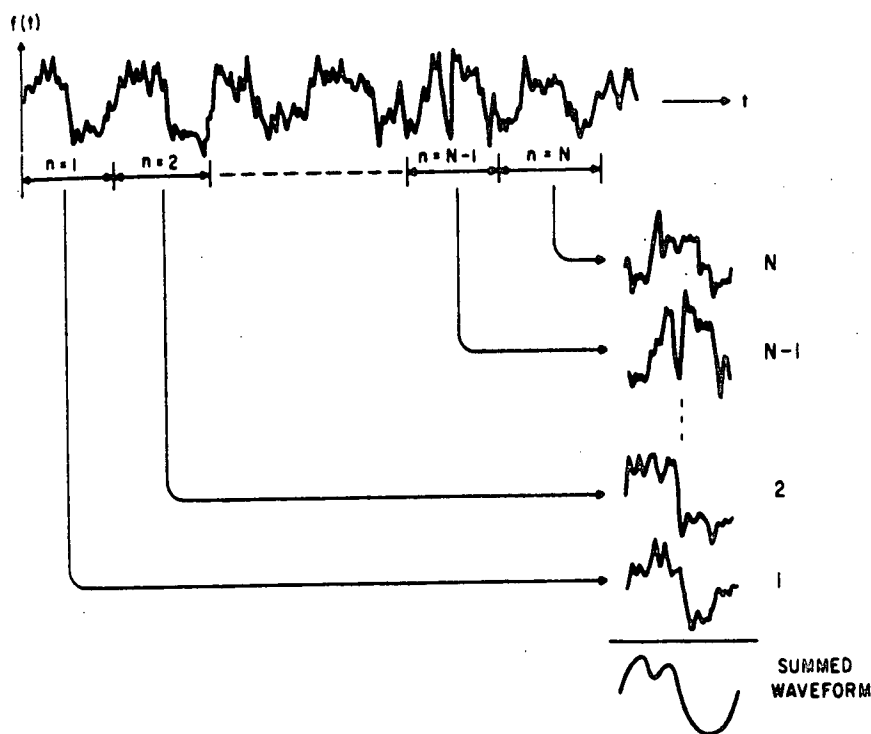
Figure 5-7. Example of Summation Averaging

If there is a signal with periodicity Ts in the input, it will sum directly as n, the number of summations, since there is coherence from one sum to the next. Signals which are incoherent (noise or signals with different repetition rate) add not as n, but as its square root. This is analogous to adding together two random signals of equal amplitude; their sum is 2 times the amplitude of either component rather than twice the size.

As a result of the difference between the rate at which coherent and incoherent signals are summed, the ratio of the wanted to unwanted signals in the sum is n times the same ratio at the input to the summation device. For most signals, on the order of 100 summations (giving a ten-to-one signal to-noise ratio improvement) are adequate to extract the wanted signal from the background.

The general organization of a device suitable for forming the function F (r) is shown in Figure 5-8. Two inputs are required: the signal itself, which may be preprocessed as has been described, and a trigger signal having the same periodicity as the signal to be extracted. In our application, the desired signal is the waveform developed by each revolution of a piece of rotating machinery, so the trigger is a once-per-revolution pulse generated by a transducer on the shaft.
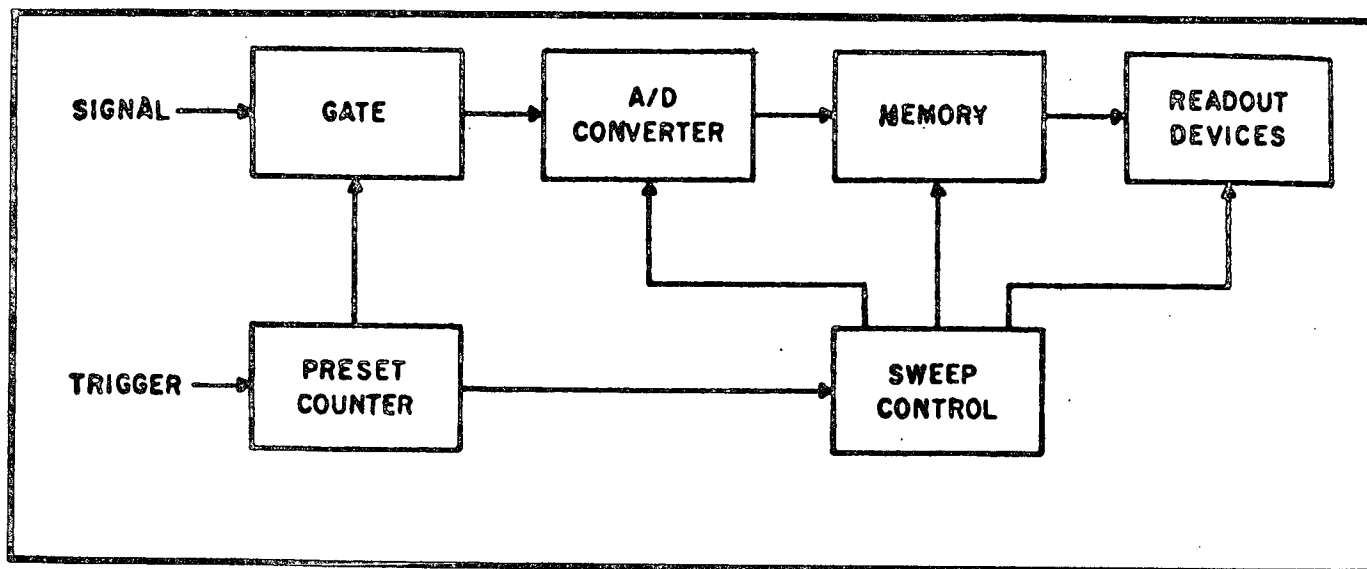
Figure 5-8.   Organization of a Summation Analyzer

The trigger signals are fed to a pre-set counter which controls a gate. If the number of trigger signals counted is less than the pre-set number, the signal to be analyzed is passed to the succeeding stages; when the pre-set number is reached, the gate opens and the summation process ceases.

The summation device itself has three major components:
- o Analog to Digital Converter
- o Memory Bank
- o Scanning Control

The heart of the analyzer is the memory, usually a bank of magnetic cores. Under the control of the scanner, the analog-to-digital converter looks at the incoming signal. The scanner then advances one step and the process repeats, with the digitized signal being stored in the second address. The process continues until all addresses have been contacted, thus storing in the memory a digitized representation of the selected portion of the incoming signal.

When another trigger pulse comes along, the process is repeated, each digitized signal being added to that already stored in the appropriate address of the memory. This continues until the pre-set counter stops the process after a predetermined number of summations.

If the signals being studied are bipolar (swing both above and below a 0 line), and have a high frequency, any jitter of the trigger pulse or speed change of the rotating machinery will cause the positive peaks and negative peaks to appear in the same position during different portions of the analysis and they will cancel. This can be avoided by rectifying the signal and then applying digital time averaging. This technique can be very useful if the speed of the rotating machinery being studied is not constant.

The transient signal, even though weak, adds energy at the same address on each summation while other non-synchronized events add randomly, first in one address then in another, etc., so that their contribution is spread out rather than concentrated. As a result, these signals with the proper period-icity are again made evident.

Addendum E contains a representative listing of summation analyzer manufacturers and Addendum F describes summation analyzers which are suitable for SBA applications.

5.3.6 CORRELATERS

Correlation is a technique whereby the similarity of the waveform of two signals may be measured. The similarity may be investigated in the time domain by determining the cross-correlation function ϕ (τ) which describes the manner in which the average value of the product $[x(t) \cdot y (t - \tau)]$ varies with the time delay τ.

Such signal processing involving filtering, phase shifting of one of the filtered signals through 90°, multiplication and time averaging, is capable of providing complete information on the phase and magnitude similarities of the signals throughout the frequency range of interest.

$$i.e. \quad \phi_{xy}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} \left[x(t) \cdot y (t - \tau) \right] dt$$

For detecting the unknown periodic signals in a noisy signal, a similar process may be carried out by multiplying the signal $x(t)$ by a time-delayed version of itself and so determining the auto-correlation function ϕ_{xx} (τ).

$$i.e. \quad \phi_{xx}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} \left[x(t) \cdot x (t - \tau) \right] dt$$

The value of this function depends not on the actual waveshape of the signal (or signals), but on the frequency content.

The similarity of two signals may also be investigated in the frequency domain by determining the power spectral density of the two signals and the cross power spectral density. These two functions are given by:

$$\begin{bmatrix} \text{Power Spectral Density} \\ \text{of signal } x(t) \text{ at} \\ \text{frequency } f \end{bmatrix} \quad W_x(f) = \lim_{\substack{\delta f \to 0 \\ T \to \infty}} \frac{1}{\delta f \cdot T} \int_{0}^{T} x_{f, \delta f}^2(f, t) \, dt$$

where $x_{f, \delta f}(f, t)$ is that part of the signal $x(t)$ contained in a narrow frequency band δf centered at frequency f.

The cross-power spectral density $W_{xy}(f)$ comprises an in phase (C_{xy}) component and a quadrature (Q_{xy}) component, i.e.:

$$\left| W_{xy}(f) \right| = \sqrt{C_{xy}^2(f) + Q_{xy}^2(f)}$$

where:-

$$C_{xy}(f) = \lim_{\substack{\delta f \to 0 \\ T \to \infty}} \frac{1}{\delta f \cdot T} \int_0^T \left[x_{f, \delta f}(f, t) \cdot y_f(f, t) \right] dt$$

and

$$Q_{xy}(f) = \lim_{\substack{\delta f \to 0 \\ T \to \infty}} \frac{1}{\delta f \cdot T} \int_0^T \left[x_f(f, t) \underline{/90^\circ} \circ y_f(f, t) \right] dt$$

$x_{f, \delta f}(f, t) \underline{/90^\circ}$ is $x_{f, \delta f}(f, t)$ phase shifted through 90°.

A measure of the magnitude similarity between the two signals is provided by the coherence function γ.

$$\gamma(f) = \sqrt{\frac{\left| W_{xy}(f) \right|}{W_x(f) \cdot W_y(f)}}$$

Measurement and processing equipment for the rapid application of correlation and spectral density techniques have received much attention in recent years and these techniques are now amendable to operational usage.

In summary, auto-correlation processing permits detection of significant internal waveform relationships. Failure mode acoustic waveforms are correlatable against normal (idealized) operation waveforms. The idealized waveform can be shifted in time relative to the actual failure mode waveforms, and when the correlation function is a maximum, the position of noise bursts will be located. By then looking between the noise peaks to determine silent periods and signal amplitudes, measuring the amplitude of existing noise bursts & identifying the largest of them, and then determining the various ratios between these measured values and finally comparing these measurements and ratios, correlation is achieved.

Addendums E & F contain, respectively, examples of correlation manufacturers and hardware suitable for SBA application.

5.3.7 DIGITAL COMPUTERS

Real-time analyzers and correlators discussed in the previous paragraphs employ digital logic and contain buffers, registers, and memory similar to that used in digital computers.

In a real-time Structure Borne Acoustic Test System, it is also necessary to utilize a general-purpose computer or processor which is not oriented toward one specific task, but may be programmed to compute and manipulate different data. The area of SBA can better be serviced by processors emphasizing particular hardware and software characteristics. The functions required of a SBA processor are identified in Figure 5-9. A detailed discussion of these functional requirements, and a preliminary exercise to size SBA processor is presented in Addendum H & Appendix C to KSC/GE Report DB72D042, See Reference 39, Section I, Addendum A.

A processor system is composed of two elements: hardware and software. A short discussion of these elements follows.

5.3.7.1 Processor Hardware

The hardware comprises the computing machine and peripheral equipment such as typewriters and tape punches. The processor is made up of five sections: input section, output section, arithmetic unit, memory, and control.

Input: The input section, in conjunction with appropriate external devices, receives data and instructions from various media (e.g., magnetic tape) or via a manual-entry keyboard. The incoming information is stored by the computer in its memory.

The basic function of the input section is to translate the external data into a form in which it can be stored in the computer memory (e.g., binary words).

Output: The output section of the processor transmits data to output devices such as typewriters, and magnetic tapes performing code translation and formulating as appropriate. The output section also transmits signals for controlling external devices; for example, function commands for instruments such as analyzers. Some peripheral units can function both as input and output devices. For example, the computer can both read from and record on, magnetic tapes.
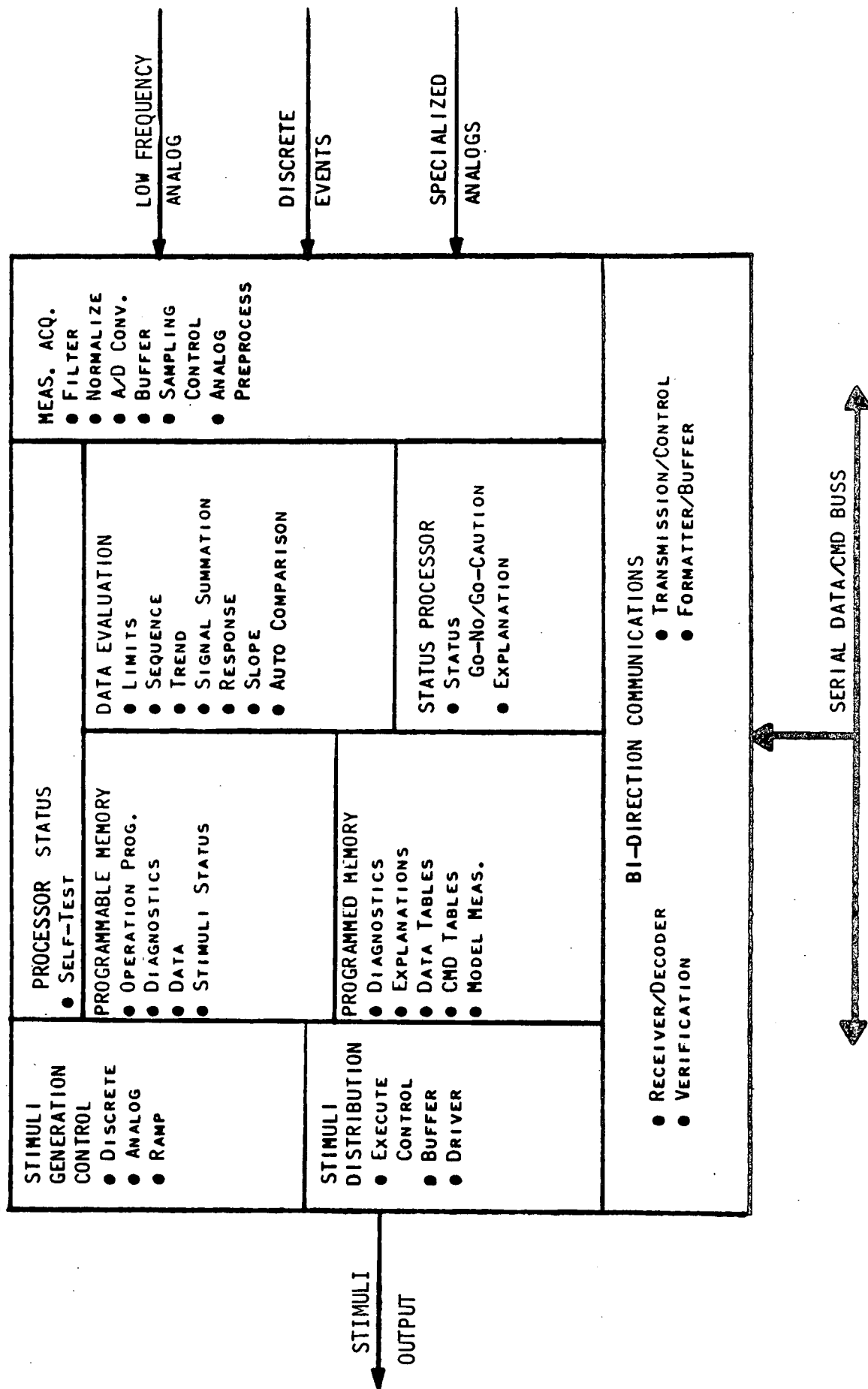
Figure 5-9.   STRUCTURE BORNE ACOUSTIC PROCESSOR FUNCTIONS

Arithmetic: The arithmetic unit performs calculations (using basic arithmetic operations) and manipulates data. Multiplication and division are accomplished either by successive additions and subtractions initiated by software, or with additional hardware, usually offered as an option.

The arithmetic unit consists of one or more registers or 'accumulators', and associated logic circuitry. The accumulators hold the results of arithmetic and logical operations performed by instructions while the logic enables data in the accumulators to be combined with information transferred from memory.

Memory: This section is the heart of the computer; all information processed by the computer passes through the memory. Besides word capacity, the speed with which information can be stored or read from memory is one of the principal characteristics defining the performance of the processor.

Control: This section controls and coordinates the whole operation of the processor. It directs the transfer of data between the registers and controls the operations performed. It also interprets the instructions read from memory and sets up the gating functions to carry out their execution.

5.3.7.2 Software

Software consists of the programs or lists of instructions that control operation of the processor; these programs are commonly recorded on punched tape or magnetic tape, and are then read into the computer through one of its input devices.

The choice of both processor hardware and software will be dictated by total system requirements. This not only includes the pertinent SBA system, but the interfacing and integration with the larger and total checkout and performance monitoring system employed by a future space program.

Even the simplest tasks involve intricate movements of numerous binary bits of information within the processor, such that explicit instructions must be given to the processor to perform each task. Therefore, while it is

D5-30

possible to write programs which are coded in the binary form the computer
uses, called "machine language", it is too time consuming and susceptible
to errors to be practical. Various aids have therefore been devised to make
programming easier, and consequently more effective.

Software is the general term given to programs which, when loaded into the
processor, utilize the hardware itself to perform all the detail work.
The purpose of software is therefore to make the computer usable.

Software can be divided loosely into four classes:
a) Translators - programs which translate human-oriented languages into
   machine language.

b) Control systems - programs which take care of all the functions essential
   to operation of the processor system.

c) Utility routines - program editors, program debugging routines, hardware
   diagnostics.

d) Applications programs - these adapt processor system for maximum effective-
   ness in a specific application.

5.4 DATA DISPLAY

There are several types of data display essential for a real-time SBA
checkout system. First, some means of visually monitoring the signals prior
to processing and of carrying out overall system calibration is highly
desirable. This type of display aids in initial SBA checkout system.
set-up and calibration. For optimum system flexibility, provisions must
be made for this type of display which includes oscillograms, spectrograms,
and chart recordings. A second type of display is operational analog record-
ings that can be stored and called up for viewing only when requested. The
final display is either digital or analog and provides an operator with
mechanical device Go,No-Go, or Caution status as defined in Chapter 3.

A wide choice of methods for final information presentation is available

and the selection will be greatly influenced by the type of acoustic signal involved, i.e., continuous, intermittent, or impulsive.

Of course, acoustic limits may be stored in the processor and the acoustic data interlocked to provide no visual display unless the data falls either into the caution or No-Go category.

A representative listing of data display equipment manufacturers is shown in Addendum E and some representative samples of this hardware are shown in Addendum F.

5.5 INSTRUMENTATION SELECTION

The principle determinants of the "Measurement System" instrumentation selection are:

1. Type, quantity, and location of mechanical devices.
2. The depth of Readiness Assessment
3. The level of mechanical system readiness assessment that will be achieved by other than SBA techniques.

Coupled with these determinants are the numerous types of hardware selections available for each element of the measurement system. The net result is a potential number of instrumentation selection combinations approaching infinity. Thus, it is impractical to pursue instrumentation selection further in this initial handbook release.

The design tradeoffs and the resulting instrumentation do, however, become apparent with the definition of the principle system determinants listed above and with the understanding of off-the-shelf equipment availability and applications. Addendum I provides a checklist to follow in both instrumentation selection and installation. The majority of instrumentation equipment required by the SBA system is commercially available equipment. There will be a requirement for a limited amount of "special design" equipment to facilitate "measurement system" linkage and data traffic control.

The bulk of SBA system design actions will concern itself with software programming to properly use the hardware in acquiring, switching, monitoring, filtering, analysing, correlating, and presenting SBA data.

CHAPTER 6
ACOUSTIC TESTING

6.1 GENERAL

In the preceding chapters, structure borne acoustics' relationship to mechanical systems readiness assessment has been defined, and SBA application/rationale, component analysis techniques, and the measurement system selection have been presented. It is currently necessary to empirically establish each mechanical component's "normal operation" acoustic signature. From this base line signature, it is possible to determine with high confidence upper and lower limits which, when exceeded, indicate abnormal operation. The establishment of these limits is possible by the statistical extrapolation of test data accumulated on previous test programs. Acoustic limit determination is discussed further in the next chapter.

Care must be taken to establish usable base line acoustic signatures. This can best be achieved by monitoring each mechanical component's acoustic signature when activated in the operational environment. An acceptable alternative is to activate the mechanical device in a test bed which simulates the operational environment. The factors that must be considered in obtaining the "normal operation acoustic signature" are treated in this chapter.

6.2 TEST SEQUENCE

To establish the acoustic signature base line for each mechanical device tested, there is a fixed sequence of activities which, if followed, will result in the most efficient collection of data. These activities and their flow sequence are shown in the SBA Test Flow Diagram, Figure 6-1.

There are 5 principal task divisions.

   I.   Obtain component and facility for achieving either actual or simulated operation.

  II.   Select, secure, and calibrate acoustic detection electronics.

 III.   Select, secure, and calibrate data processing electronics.

 IV.   Conduct acoustic tests and record signature.

  V.   Reduce and evaluate data and establish acoustic limits.

These divisions and sub-tasks are delineated in Figure 6-1. This flow diagram is self-explanatory with the exception of the term "test set up". Within the context of this handbook, "test set up" has a dual meaning. Test set up can mean either the normal operational installation of a mechanical component or installation in a simulated operational environment or test bed.

6.3 FACILITY REQUIREMENTS

Where it is feasible to monitor and obtain the normal acoustic signature of a mechanical component in an operational habitat, the only additional facility requirements imposed by implementing this non-destructive test technique is that required by the "Measurement System". This "Measurement System" was thoroughly discussed in the previous chapter.

Figure 6 2 is a photograph of a General Electric Company Spectrum Analysis facility. This provides a physical concept of "Measurement System" hardware. However, this facility must service a complete range of research and development signature analysis problems. Applications other than mechanical device acoustics investigated with this equipment includes heart sounds, noise suppressor problems and speech recognition. Hence, the need for eight racks of diagnostic equipment.

Where a special test bed must be employed to simulate the component operational environment, additional expense,time and hardware is obviously required. Where a large number of components will be tested, this cost can be amortized to a very small per component cost. This is possible by multiple use of a common test bed. For example: A special facility test set-up was designed and built by General Electric as a means of studying the acoustic signatures of five mechanical components under simulated operating conditions. This test
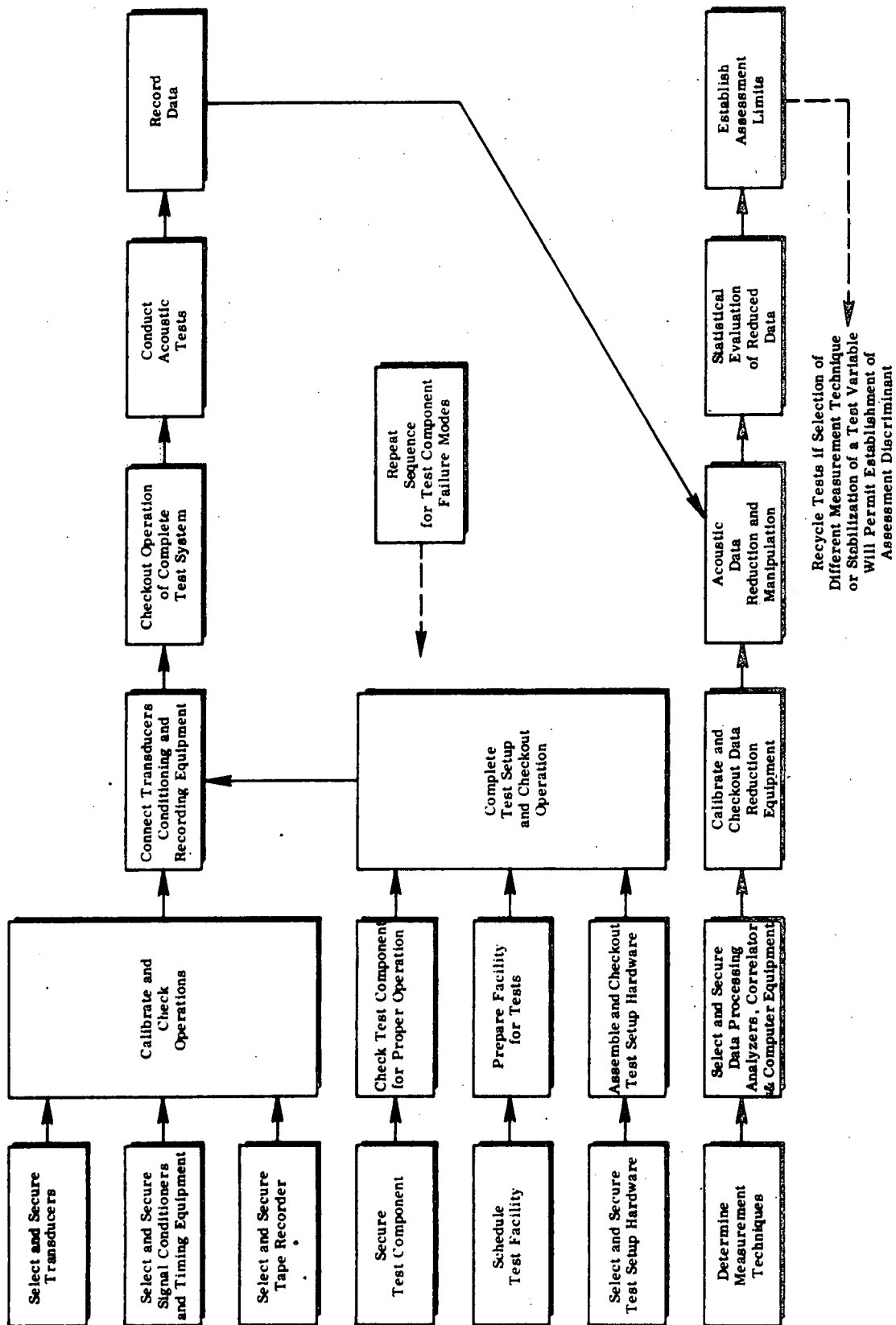
Figure 6-1. Structure Borne Acoustic Test Flow Diagram

Figure 6-2. Spectrum Pattern Analysis Facility

A   35 mm Recording Camera and Film Processor
    Allen Dumont 304-AR and Auxilliary Equipment
B   Oscilloscope and Auxilliary Equipment
C   Analogue Magnetic Tape Recorder
D   Analogue Magnetic Tape Recorder Sangamo 4700

E   R&D Center Frequency Analyzer (80 Filters)
F   Spectrum Analysis Power Supplies/Misc Equipment
G   R&D Center Frequency Analyzer (200 Filters)
H   Digital Magnetic Tape Recorder
I   Varian 620i Minicomputer Rack

set-up (see Figure 6-3) provided for ready installation and quick replacement of the test components. This test set-up, as now established, could accommodate the testing of many different components with only minor modifications. These test facilities located at General Electric's Research and Development Laboratory, Schenectady, New York, were employed for this test program. Approximately 80 square feet of space was used for a work bench and test set-up facilities to acquire magnetic tape recordings of the component acoustic signatures. Facilities temperature range of $65^\circ \pm 5^\circ F.$, humidity range of 45 ± 5 percent and normal open laboratory cleanliness and lighting were maintained.

6.4 TEST PLANNING

To assure maximum benefits from acoustic testing, it is necessary to plan the particulars of each test. The Test Plan should at a minimum include the following:

    I. INTRODUCTION
          1.1 Purpose and Scope of Test
          1.2 Pertinent Test Ground Rules

    II. GENERAL
          2.1 Component Identification
          2.2 Test Set-Up Hardware Description
          2.3 Test Flow
          2.4 Test Schedule
          2.5 Documentation Requirements

    III. TEST FACILITY IDENTIFICATION

    IV. DETAILED TEST PROCEDURE
          4.1 Test Sequence
          4.2 Test Set Up
          4.3 Component Checkout Test Procedure
          4.4 Acoustic Instrumentation
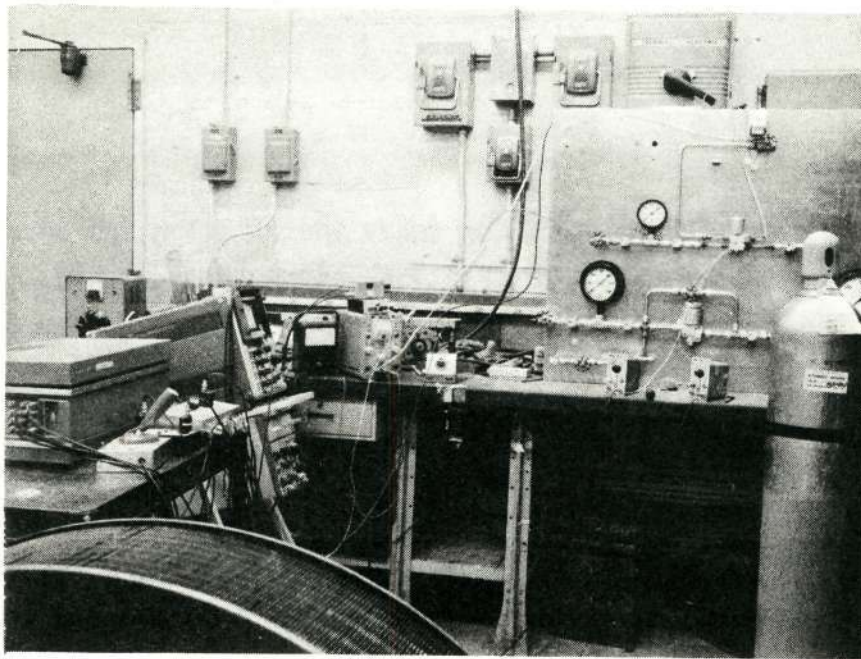
View A
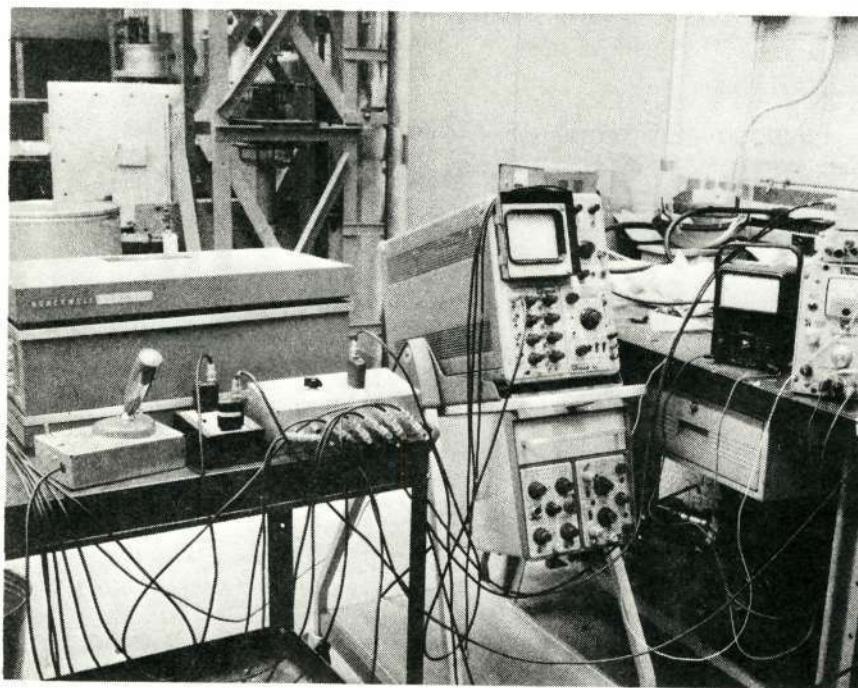
View B

Figure 6-3. Test Set Up

4.5 Test System Calibration Checkout

4.6 Acoustic Test & Data Recording

4.7 Measurement Techniques

4.8 Limit Determination

A sample test plan used for acoustic testing of a solenoid valve is contained in Addendum C. While it may not be necessary to formalize all aspects of each component test plan, the test plan is highly recommended as part of the total "methodology" which will ultimately save much wasted effort and back-tracking.

CHAPTER 7

INTERPRETATION OF MEASUREMENT DATA

7.1 GENERAL

The central problems involved in the evaluation of component condition using SBA are these:

- o Identification of the discriminants which characterize the condition of the component undergoing test
- o Selecting the optimum technique(s) to extract the data which best characterizes the condition of the component undergoing test
- o Relating the acoustic data to the events taking place within the component undergoing test
- o Establishing the qualitative characteristics or quantitative values for the processed data which relate to a Go, Caution or No-Go component

It is the latter two problems which will be examined in this chapter.

7.2 ACOUSTIC LIMIT DETERMINATION

7.2.1 GENERAL

To establish acoustic limits for component Go, Caution or No-Go status, the acoustic data must be related to the physical events taking place within the component. Further, to establish quantitative values of Go, Caution or No-Go, an analogy between the acoustic signal parameters and the components' operating parameters must be drawn. At the present state of the art, these relationships are derived from the testing previously described. With experience and refinement in the analytical process it will be possible to minimize the required testing.

7.2.2 NOMINAL OPERATION

A normal operational profile, in acoustic terms, is established through controlled testing of known, fully operational components. Obviously, during the component testing, there must be sufficient instrumentation, in addition to the acoustics, to permit quantitative relating of such things as

flow, noise, pressure, RPM and timing to the acoustic signals.

From a component fault tree, those parameters necessary to characterize component operation can be identified. Again taking the 75M08825 solenoid valve as an example, refer to the failure mode tree on Figure 4-3. The failure modes identified are:

o   fails to deactuate

o   fails to actuate

o   erroneous indication

o   venting to atmosphere (leakage)

o   sluggish operation

Of the five failure modes, the first three are discrete events which either occur or do not occur. For these it is only necessary to establish that the event did or did not take place. The remaining two require comparison of actual value versus predetermined limits to permit Go, Caution or No-Go decisions.

If the solenoid valve actuates/deactuates as commanded, provides the proper position indication, does not leak and operates within a normal time frame, confidence in the operational integrity would be very high. Therefore, to be useful the acoustic signature must provide information which can be related to component operation to establish the operational integrity.

The raw data necessary for determination of nominal limits are obtained during component testing discussed in the preceding chapter. Determination of numerical values is discussed in Paragraph 7.4.

7.2.3   FAILURE MODE OPERATIONS

In the case of failure mode operations, failures are introduced into the device and testing similar to nominal repeated.

Component data characterizing failed or degraded components are more difficult to derive during testing similar to that for nominal operation. The factors which present rather severe complications are:

o   Specifications rarely clearly identify the transition between
    Go and Caution and between Caution and No-Go or the quantitative

range for each. This is complicated by the fact that frequently the Go, Caution or No-Go criteria will vary due to the operational application of the mechanical device.

o   It is very difficult to install truly representative failures; that is, introduced failures rarely duplicate "natural" failures.

o   When disassembling a device to introduce a failure, a danger exists that another unknown effect will be introduced, thereby introducing a bias which can easily produce unwarranted or incorrect conclusions based on the acoustic data.

Therefore, in general, the determination of Caution and No-Go limits by simulating failures is not recommended due to the cost and probability of introducing an unknown bias into the testing. This philosophy holds where a change in the characteristic acoustic signature is detected to exceed a boundary or limit and is thereby detected as a No-Go or Caution.

Where the signature characteristic which indicates a failure does not exist in a normal signature, testing will be required. For example, the acoustic signature for a component in a Go condition does not contain a leakage characteristic. Therefore, it will be necessary to introduce a leakage failure into the component to establish the signature characteristic of leakage. Due to the difficulty of identifying leakage using SBA techniques any leakage detected using SBA would be classified as Caution or No-Go.

7.2.3   RELATIONSHIP TO OPERATIONAL LIMITS
Just as a thermocouple produces a signal proportional to temperature, the acoustic accelerometer produces a signal proportional or analgous to the sound produced in a mechanical device. To make an operational decision a relationship must first be established between the thermocouple output and the temperature. Second, the Go, Caution and No-Go criteria must be established relative to thermocouple voltage. This same logic process applies to the necessity for relating acoustic signals to physical events, processes and limit criteria.

Component analysis, discussed in Chapter 4, resulted in the identification of component failure modes, the internal reactions which form the acoustic signature, and a predicted signature for normal operation. As a further

extension of this process, each failure mechanism and mode should be examined to identify failure mechanism impact on the nominal signature. That is, how will the failure mechanism change the acoustic signature.

Table 7-1 tabulates briefly the effects of failure modes and mechanisms upon the noise produced within the solenoid valve. The definition available from this approach is primarily a function of insight and experience. The purpose of the exercise is to sharpen the analytical capability when relating acoustic data to the noise sources.

Acoustic data can be processed into a limited number of formats involving frequency, amplitude, and time. Typical formats in general use include:
  o Time vs. Amplitude
  o Frequency vs. Amplitude
  o Time vs. Frequency vs. Amplitude (intensity modulated)

Of the three parameters - time, frequency and amplitude - time repeatability for a specific event generally has the smallest variation. Frequency has the next smallest dispersion and amplitude variations are the least reliable parameter for detecting valid changes. Amplitude, of course, is very important for determination of timing intervals.

The key feature or characteristic of the acoustic signal which provides the component operational condition may take a number of forms such as:
  o Presence or absence of a discrete frequency or band
     of frequencies
  o Signal amplitude rate of change for a given frequency
  o Frequency rate of change
  o Signal amplitude correlation with a constant value
     or a variable function
  o Absolute or relative timing
  o Average or RMs amplitude of a given frequency or
     frequency band
  o Peak vs. RMS amplitude comparison

The key feature which best displays the operational condition should be selected and, where applicable, reduced to numerical values for statistical manipulation, as described in paragraph 7.4. For a discrete feature, e.g.,

D7-4

actuation of a value, it is only necessary to establish the presence of a signal feature which indicates that the prescribed action has taken place.

In many cases it is not necessary to establish numerical No-Go values for a given feature or characteristic. For example, the fully loaded shaft RPM of a cyclic device may be defined in the component specification data. It is then only necessary to select the acoustic signal characteristic which can be related to shaft RPM. Unfortunately, quantitative characteristics are frequently left unspecified, particularly in regard to allowed leakage.

7.3   TREND ANALYSIS

Trend analysis requires the use of several values of a parameter as a basis to detect high rates of change, abrupt departures from steady state conditions and gradual drifts toward an out-of-tolerance condition. The occurrence of one of these conditions does not necessarily presage a component malfunction. It should, however, raise questions as to why the change has occurred.

The noted change would, in general, require correlation with some other system or component parameter to insure that a false alarm is not generated. Investigation of the change could provide many different causes.

- o   The component has, in fact, degenerated
- o   A system defect outside the instrumented component is responsible
- o   A normal, explainable pertubation has taken place within the component and/or system

Trend analysis, by its nature, requires a time base; i.e., sampling over a period of time to establish rate of change. This in turn requires a memory device for evaluation purposes.

Possibilities for placing limits and providing alarms based on trend data are varied. Common methods include the specification of:

- o   Allowable parameter change with respect to time
- o   Number of transient excursions outside a band of valves
- o   Duration of transient excursions outside a band of valves

Trend analysis is best accomplished through the use of computation equipment where predetermined rate, number or duration of parameter excursions can be stored for tabulation and comparison purposes. Detection of rapid changes within a normal band of values as well as a definite drift toward an out-of-tolerance condition is a valuable indicator of an incipient problem. Detection of such a trend can provide a Caution flag long before a warning is received based on exceeding the absolute value of a parameter which defines a Caution status.

7.4   STATISTICAL "LIMIT" DECISION MAKING
7.4.1   GENERAL
Statistics is a valuable management tool for decision-making in any sort of readiness assessment instrumentation system. This usefulness lies in two major areas:

> o   Determination of quantitative values for Go, Caution, and No-Go based on component test data
> o   Analysis of component operational data, subsequent to limit determination, to establish significant trends,

7.4.2   STATISTICAL DETERMINATION OF GO, CAUTION AND NO-GO
7.4.2.1   General
As previously discussed, the determination of Caution or No-Go limits through introduction of defects into components for SBA testing is at best difficult and time consuming. This is brought about by the high probability of affecting the component in an unanticipated manner when introducing the defect or the possibility that the simulation is not representative of the defect for which simulation is attempted. Therefore, the technique having the greater probability for success involves determination of the quantitative values of each discriminant which characterize a Go condition and applying statistical techniques to establish Caution and No-Go values.

The SBA elements which must be accomplished to implement the statistical approach for normal (Go) components are:

> o   Component analysis to:
>> -   Establish failure modes
>> -   Identify noise sources
>> -   Identify discriminants

o   Select the processing technique most definitive

o   Process the SBA to establish numerical values for each
    discriminant

o   Apply tolerance limit technique to establish Go, Caution
    and No-Go values.

7.4.2.2 Data Mean ($\bar{x}$), Standard Deviation(s)

Having secured numerical data through the preceding approach it is necessary
to establish the nominal Go values for the discriminant. A histogram plot
of the data, depending upon the spread of values, can provide a good and
perhaps adequate definition of the Go values. A histogram is a frequency
distribution in bar chart form. Take, for example, the operating times, in
milliseconds (ms), for a solenoid value shown in Table 7-1.

38.	37.6	37.2	39.4
38.	37.8	37.2	38.
38.	38.3	38.	38.8
37.	39.2	36.	39.
38.4	38.6	37.	38.6
38.	38.7	36.8	37.4
38.1	38.1	38.6	37.
38.4	37.	37.2	39.
39.2			

TABLE 7-1

SOLENOID VALVE OPERATING TIMES (In Milliseconds)

A histogram is prepared by ordering (arranging in ascending times) and
plotting frequency of occurrence in 0.5 millisecond increments (per Table
7-2).

Time Span	Number of Occurrences
36.0 - 36.49	1
36.5 - 36.99	1
37.0 - 37.49	8
37.5 - 37.99	2

Time Span	Number of Occurrences
38.0 - 38.49	10
38.5 - 38.99	6
39.0 - 39.49	5

TABLE 7-2

TIME SPAN vs. FREQUENCY OF OCCURRENCE

A histogram of Table 7-2 data is shown in Figure 7-1.
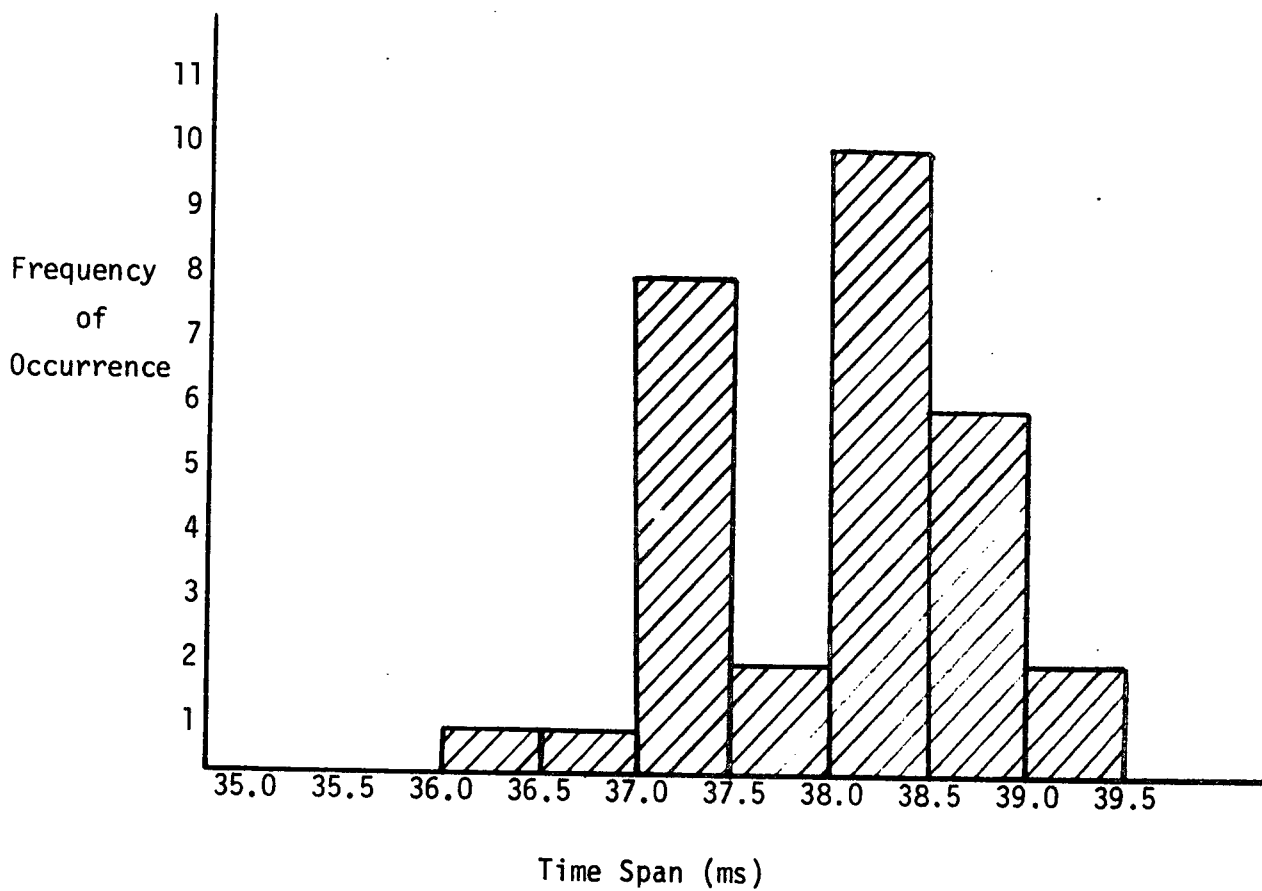
FIGURE 7-1

HISTOGRAM OF SOLENOID VALVE OPERATING TIMES

As a practical matter, one could reasonably conclude that an operating time greater than 40 ms or less than 35 ms would certainly be unexpected and might require further investigation.

However, for a more rigorous approach the mean $\overline{X}$ and the sample standard deviation(s) are calculated.

$$\overline{X} = \frac{\text{Sum of All Times}}{\text{Number of Values}} = \frac{1254}{33} = 38.0 \text{ ms}$$

$$s = \sqrt{\frac{\text{Sum of Each }(X-\overline{X})^2}{\text{Number of Values-1}}} = \sqrt{\frac{22.21}{32}} = .83$$

The significance of s is that for a normal distribution (Gaussian):

o   68% of the area under the curve is contained in the interval between the mean and $\pm$ the standard deviation

o   95% for $\pm$ 2 standard deviations

o   99.7% for $\pm$ 3 standard deviations

There is an underlying assumption, based on the Central Limit Theorem, that the data to be treated are from a normal distribution. Verification of probable normality of this data can be demonstrated by a plot on normal distribution probability paper, or by using the $W_n(N)$*test for normality.

Confidence limits are intervals intended to include the true mean (u) with a stated probability. Frequently only the sample mean (i.e., mean of the sample data) is known. The sample mean (e.g., $\overline{X}$) is an estimate of the unknown population or true mean, u, but differs due to sampling variation.** It is possible, however, to construct a statistical interval known as a confidence interval for the population mean, u. As an example, a 90% confidence interval on the true mean (knowing only $\overline{X}$) is an interval which contains u with a probability of 0.90. A moderate deviation of the data from normality will have little impact on confidence interval determinations concerning a population mean.

*   Addendum A, Section I, No. 37

** Likewise, the sample standard deviation s, is an estimate of the unknown population or true standard deviation, σ.

For the purposes of establishing Go limits we are more interested in specifying an interval in which a specified proportion, for example 90%, of all values will fall. For a normal distribution, if u and σ are known rather than $\overline{X}$ and s, 90% of the population is located in the interval: $u \pm 1.64\sigma$.

If only $\overline{X}$ and s are known then we can only specify a probability, e.g., 95%, that the interval contains 90% of the population. This interval is called a tolerance interval.

In the absence of other guidelines the following is recommended for establishing Go, Caution and No-Go values for a given discriminant based on 30 operations of the tested component in its operational environment.

      o   Calculate $\overline{X}$

      o   Calculate s

Go condition for X values between $\overline{X}$ and $\pm (2.14)(s)$

Caution condition for X values outside the Go limits but within $\overline{X} \pm 3.35(s)$

No-Go condition for X values outside the Caution limits

For the solenoid valve:

    Go = $38 \pm (2.14)(.83)$ = 38 ± 1.78 = 36.22 - 39.78

    Caution: $38 \pm 3.35(.83)$ = 38 ± 2.78 = 35.22 - 40.78

    Therefore the Caution values are: 40.78 to 39.78
                                      and 36.22 to 35.22

    No-Go: Above 40.78, Below 35.22

7.4.3 STATISTICAL ANALYSIS OF TRENDS

The principal aspects of analysis for component performance trends are:

      o   Routine periodic sampling of those discriminants which characterize the operation of the instrumented component

      o   Processing and presentation of the data in a way which provides quantitative values of the discriminants

o   A means for making appropriate decisions regarding the
     operational integrity of the instrumented component

The first two aspects have been discussed previously. The third can be
treated similarly to control chart techniques forming a part of statistical
quality control. The control chart technique, which, in the quality control
domain can be manual or electronically processed indicates that one of the
most common types of control charting is that based on the sample average
($\overline{X}$) made during a sampling period. Though for quality control purposes the
sampling is based on individual samples from a number of separate components,
the technique is appropriate for readiness assessment where sequential sam-
ples are taken from a single device.

The values of $\overline{X}$ taken over successive sampling periods are plotted against
time. When repetitive samples of N observations are taken from a stable
normal or near normal distribution the average, $\overline{X}$, for these samples tend
to be normally distributed about a mean u with a standard deviation
$\sigma_{\overline{X}} = \sigma/\sqrt{n}$ where n equals the number of samples per sampling period,
with an estimate for σ (s) established during component testing dis-
cussed in paragraph 7.4.2. If the device provides a stable population the
variability of the sample averages, $\overline{X}$, of successive sampling periods can
be predicted. The resulting $s/\sqrt{N}$ provides the basis for predicting that
about 95% of the $\overline{X}$'s should lie within a band of width $\pm 2s/\sqrt{N}$ and essent-
ially all should fall between $\pm 3s/\sqrt{N}$.

Suppose, however, that instabilities appear during successive sampling
periods (rather than the less likely instability of successive samples with-
in the same sampling period). If so, these instabilities will manifest
themselves by the variation of the sampling period $\overline{X}$'s and exceed that predicted
on the basis of the variation of X within a sampling period. That is, the
presumption is made that during a relatively short period the discriminant
is essentially stable.

Processing the data for a routine such as that described would take the
following form:

Sampling Period	Observation					$\bar{X}$
	A	B	C	D	E	$\bar{X}_1$
(1)	a_1	b_1	c_1	d_1	e_1	$\bar{X}_2$
(2)	a_2					
(3)	a_3					
.	a_4					
.	.					
.	.					
.	.					
n	a_n					$\bar{X}_n$

$$\text{Total} =$$

$$\text{Average } \left(\frac{\text{Total}}{N}\right) = \bar{X}$$

The range for which the component discriminant is defined to be a Go value
is described by the relation:

$$\bar{X} \pm 3s / \sqrt{n} \qquad \text{(n = 5 in the above example;}$$

$$\text{s developed during component testing)}$$

Decision making, using the above technique, takes essentially the following
approach:
A new data value is subtracted from the mean and the difference compared
with the three sigma(s) limits of the variab℩... If the comparison shows
the difference (mean — data value) to be less than 3s the information is
discarded. If the comparison shows the difference to be greater than 3s a
count is registered. If the count register exceeds a given number for the
sample set a new mean and variance (s^2) is calculated.

A new value for the mean indicates a persistently out-of-tolerance condition
greater than 3s over the time span for the sample set. If this out-of-
tolerance condition recurs over several sets, then a trend is indicated.
A No-Go or Caution condition would be indicated when the latest mean cal-
culation differs from a preset mean or when the mean's rate of change
exceeds a predetermined value.

D7-12

Additional facets of the above technique should be stressed:

o Using either manual or automatic processing, the Go, No-Go
   and Caution quantitative values can be developed through pro-
   cessing the acoustic data for several operations of the com-
   ponent. Then, as the component continues to operate, these
   operational limits are adjusted by the incoming data. This
   iterative process permits establishing operational parameters
   in-line, rather than in a component test program.

o The trend portion of this technique can be circumvented
   and the Go, Caution or No-Go decision based on finite limits
   without the recomputation of the mean. This, then, is essent-
   ially the technique described in paragraph 7.4.2.

ADDENDUM A

REFERENCES

Section I of this Addendum lists general "Structure Borne Acoustics" references. Section II contains a listing of acoustic and mechanical shocks; vibration standards which can be purchased from the American National Standards Institute, 1430 Broadway, New York, New York, 10018.

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SECTION II

S1.1-1960	Acoustical Terminology
S1.2-1962	Physical Measurement of Sound
S1.6-1960	Preferred Frequencies for Acoustical Measurements
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S2.2-1959	Calibration of Shock and Vibration Pickups
S3.4	Computation of the Loudness of Noise
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ISO/R495-1966	Test Codes for Measuring the Noise Emitted by Machines

ADDENDUM B

DEFINITIONS

Acceleration*

Acceleration is a vector that specifies the time rate of change of velocity.
Note 1: Various self-explanatory modifiers such as peak, average, rms are often used. The time interval must be indicated over which the average (for example) was taken.
Note 2: Acceleration may be (1) oscillatory, in which case it may be defined by the acceleration amplitude (if simple harmonic) or the rms acceleration (if random), or (2) non-oscillatory, in which case it is designated "sustained" or "transient" acceleration.

Analyzer

An analyzer is a combination of a filter system and a system for indicating the relative energy that is passed through the filter system. The filter is usually adjustable so that the signal applied to the filter can be measured in terms of the relative energy passed through the filter as a function of the adjustment of the filter response-vs-frequency characteristic. This measurement is usually interpreted as giving the distribution of energy of the applied signal as a function of frequency.

Caution

The component can perform the intended function within operational limits but performance degradation has been sensed.

Cyclic Action Component

A device in which the operational events repeat at prescribed intervals e.g., an internal combustion engine.

Confidence Limits

Confidence limits are the upper and lower values of the range over which a given percent probability applies. For instance, if the chances are 99 out of 100 that a sample lies between 10 and 12, the 99% confidence limits are said to be 10 and 12.

Critical Speed

Critical speed is a speed of a rotating system that corresponds to a resonance frequency of the system.

Decibel*

The decibel is one-tenth of a bel. Thus, the decibel is a unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power.
Note 1: Examples of quantities that qualify are power (any form), sound pressure squared, particle velocity squared, sound intensity, sound energy density, voltage squared. Thus the decibel is a unit of sound-pressure-squared level; it is common practice, however, to shorten this sound pressure level because ordinarily no ambiguity results from so doing.

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*This material is reproduced from the American Standard Acoustical Terminology, S1.1-1960

Db-1

Note 2: The logarithm to the base the tenth root of 10 is the same as ten times the logarithm to the base 10: e.g., for a number x^2, $\log_{10}^{0.1}x^2 = 10 \log_{10}x^2 = 20 \log_{10}x$. This last relationship is the one ordinarily used to simplify the language in definitions of sound pressure level, etc.

Directivity Factor*

(1) The directivity factor of a transducer used for sound emission is the ratio of the sound pressure squared, at some fixed distance and specified direction, to the mean-square sound pressure at the same distance averaged over all directions from the transducer. The distance must be great enough so that the sound appears to diverge spherically from the effective acoustic center of the sources. Unless otherwise specified, the reference direction is understood to be that of maximum response.
(2) The directivity factor of a transducer used for sound reception is the ratio of the square of the open-circuit voltage produced in response to sound waves arriving in a specified direction to the mean-square voltage that sould be produced in a perfectly diffused sound field of the same frequency and mean-square sound pressure.
Note 1: This definition may be extended to cover the case of finite frequency bands whose spectrum may be specified. Note 2: The average free-field response may be obtained, for example:
(1) By the use of a sperical integrator
(2) By numerical integration of a sufficient number of directivity patterns corresponding to different planes, or
(3) By integration of one or two directional patterns whenever the pattern of the transducer is known to possess adequate symmetry.

Discriminant

Characteristics of a device which can be correlated with the devices operational condition or performance.

Effective Sound Pressure (Root-Mean-Square Sound Pressure)*

The effective sound pressure at a point is the root-mean-square value of the instantaneous sound pressures, over a time interval at the point under consideration. In the case of periodic sound pressures, the interval must be an integral number of periods or an interval long compared to a period. In the case of non-periodic sound pressures, the interval should be long enough to make the value obtained essentially independent of small changes in the length of the interval.

Note: The term "effective sound pressure" is frequently shortened to "sound pressure."

Failure Cause
The basic anomaly which produces a failure mechanism e.g., contamination, corrosion, wear.

Failure Mechanism
Identification of the piece part which failed and the specific problem. The result of a basic anomaly which produces a failure mode e.g., a sticking valve poppet due to contamination.

Failure Mode
The form in which a component failure is manifested, e.g., fails to operate.

FARADA
Failure Rate Data fox electrical, electronic, mechanical, hydraulic, pneumatic, pyrotechnic, et. al., compiled and published by the Naval Fleet Missile System Analysis and Evaluation Group, Corona, California.

Flow Noise Generator
A mechanical component whose acoustic signature is produced primarily as a result of medium flow. Flow noise generators are generally operated on demand due to unequal pressures e.g., regulator, check valve, relief valve

Go
The operational readiness of a device which indicates a fully operational status without detection of degradation.

Impact*
An impact is a single collision of one mass in motion with a second mass which may be either in motion or at rest.

Intensity (of Sound)
The amount of acoustic energy passing perpendicularly through a unit area in unit time.

Intensity Level
Logarithmic ratio (INDB) of sound intensity with respect to a reference (10^{-12} watts per square meter).

Loudness*
Loudness is the intensive attribute of an auditory sensation, in terms of which sounds may be ordered on a scale extending from soft to loud.
Note: Loudness depends primarily upon the sound pressure of the stimulus, but it also depends upon the frequency and wave form of the stimulus.

Loudness Level*
The loudness level of a sound, in phons, is numerically equal to the median sound pressure level, in decibels, relative to 0.0002 microbar, of a free progressive wave of frequency 1000 Hz presented to listeners facing the source, which in a number of trials is judged by the listeners to be equally loud.

Note: The manner of listening to the unknown sound, which must be stated, may be considered one of the characteristics of that sound.

Masking*

(1) Masking is the process by which the threshold of audibility for one sound is raised by the presence of another (masking) sound.

(2) Masking is the process by which the threshold of audibility of a sound is raised by the presence of another (masking) sound. The unit customarily used is the decibel.

Mechanical Shock

Mechanical shock occurs when the position of a system is significantly changed in a relatively short time in a non-periodic manner. It is characterized by suddenness and large displacement, and develops a significant inertial forces in the system

Microbar, Dyne Per Square Centimeter*

A microbar is a unit of pressure commonly used in acoustics. One microbar is equal to 1 dyne per square centimeter.

Note: The term "bar" properly denotes a pressure of 10^6 dynes per square centimeter. Unfortunately, the bar was once used to mean dyne per square centimeter, but this is no longer correct.

No — Go

The operational readiness of a device which indicates that the device is not capable of performing within normal operational limits.

Noise*

(1) Noise is any undesired sound. By extension, noise is any unwanted disturbance within a useful frequency band, such as undesired electric waves in any transmission channel or device.

(2) Noise is an erratic, intermittenty, or statistically random oscillation.

Note 1: If ambiguity exists as to the nature of the noise, a phrase such as "acoustic noise" or "electric noise" should be used.

Note 2: Since the above definitions are not mutually exclusive, it is usually necessary to depend upon context for the distinction.

Noise Level*

(1) Noise level is the level of noise, the type of which must be indicated by further modifier or context.

Note: The physical quantity measured (e.g. voltage), the reference quantity, the instrument used, and the bandwidth or other weighting characteristic must be indicated.

(2) For airborne sound unless specified to the contrary, noise level is the weighted sound pressure level called sound level; the weighting must be indicated.

Octave*

(1) An octave is the interval between two sounds having a basic frequency ratio of two.
(2) An octave is the pitch interval between two tones such that one tone may be regarded as duplicating the basic musical import of the other tone at the nearest possible higher pitch.
Note 1: The interval, in octaves, between any two frequencies is the logarithm to the base 2 (or 3.322 times the logarithm to the base 10) of the frequency ratio.
Note 2: The frequency ratio corresponding to an octave pitch interval is approximately, but not always exactly 2:1.

Operational Effect

Failure mode impact on the operational readiness of a mechanical device — Go, Caution or No — Go.

Peak-To-Peak Value*

The peak-to-peak value of an oscillating quantity is the algebraic difference between the extremes of the quantity.

Power Level

Power level, in decibels, is 10 times the logarithm to the base 10 of the ratio of a given power to a referenced power. The reference power must be indicated. (The reference power is taken as 1.0×10^{-12} watt in this handbook.)

Pressure Spectrum Level*

The pressure spectrum level of a sound at a particular frequency is the effective sound pressure level of that part of the signal contained within a band 1 cycle per second wide, centered at the particular frequency. Ordinarily this has a significance only for sound having a continous distribution of energy within the frequency range under consideration. The reference pressure should be explicitly stated.

Primitive Period (Period)*

The primitive period of a periodic quantity is the smallest increment of the independent variable for which the function repeats itself.
Note: If no ambiguity is likely, the primitive period is simply called the period of the function.

Random Noise*

Random noise is an oscillation whose instantaneous magnitude is not specified for any given instant of time. The instantaneous magnitudes of a random noise are specified only by probability distribution functions giving the fraction of the total time that the magnitude, or some sequence

of magnitudes, lies within a specified range.

Note: A random noise whose instantaneous magnitudes occur according to Gaussian distribution if called Gaussian random noise.

Resonance*

Resonance of a system is forced oscillation exists when any change however small in the frequency of excitation causes a decrease in the response of the system.

Note: Velocity resonance, for example, may occur at a frequency different from that of displacement resonance.

Response*

The response of a device or system is the motion (or other output) resulting from an excitation (stimulus) under specified conditions.

Note 1: Modifying phrases must be prefixed to the term response to indicate kinds of input and output that are being utilized.

Note 2: The response characteristic, often presented graphically, gives the response as a function of some independent variable such as frequency or direction. For such purposes it is customary to assume that other characteristics of the input (for example, voltage) are held constant.

Reverberation*

1. Reverberation is the persistence of sound in an enclosed space, as a result of multiple reflections after the sound source has stopped.

2. Reverberation is the sound that persists in an enclosed space, as a result of repeated reflection or scattering, after the source of sound has stopped.

Note: The repeated reflections of residual sound in an enclosure can alternatively be described in terms of the transient behavior of the modes of vibration of the medium bounded by the enclosure.

Simple Sound Source*

A simple sound source is a source that radiates sound uniformly in all directions under free-field conditions.

Sone*

The sone is a unit of loudness. By definition, a simple tone of frequency 1000 Hz, 40 decibels above a listener's threshold, produces a loudness of 1 sone. The loudness of any sound that is judged by the listener to be n times that of the 1-sone tone is n sones.

Note 1: A millisone is equal to 0.001 sone.

Note 2: The loudness scale is a relation between loudness and level above threshold for a particular listener. In presenting data relating loudness in sones to sound

	pressure level, or in averaging the loudness scales of several listeners, the thresholds (measured or assumed) should be specified.
Sonics*	Sonics is the technology of sound in processing and analysis. Sonics includes the use of sound in any noncommunication process.
Sound*	1. Sound is an oscillation in pressure, stress, particle displacement, particle velocity, etc., in a medium with internal forces (e.g elastic, viscous), or the superposition of such propagated alterations. 2. Sound is an auditory sensation evoked by the oscillation described above. Note 1: In case of possible confusion the term "sound wave" or "elastic wave" may be used for concept (1), and the term "sound sensation" for concept (2). Not all sound waves can evoke an auditory sensation: e.g. ultrasound. Note 2: The medium in which the source exists is often indicated by an appropriate adjective: e.g airborne, waterborne, structureborne.
Sound Intensity*	The sound intensity is a specified direction at a point is the average rate of sound energy transmitted in the specified direction through a unit area normal to this direction at the point considered.
Sound Level*	Sound level is a weighted sound pressure level obtained by the use of metering characteristics and the weighting specified in the American Standard Sound Level Meters for Measurement of Noise and Other Sounds, Z24.3-1944 or the latest approved revision thereof. The weighting employed must always be stated. The reference pressure is 0.0002 microbar. Note: A suitable method of stating the weighting is, for example, "The A sound level was 43 dB."
Sound Pressure Level*	The sound pressure level, in decibels, of a sound is 20 times the logarithm to the base 10 of the ratio of the pressure of this sound to the reference pressure. The reference pressure shall be explicity stated. Note 1: The following reference pressures are in common use: (a) 2×10^{-4} microbar (b) 1 microbar

Reference pressure (a) is in general use for measurements concerned with hearing and with sound in air and liquids, while (b) has gained widespread acceptance for calibrations of transducers and various kinds of sound measurements in liquids.
(The reference pressure used in this handbook is 2×10^{-4} microbar = 20 N/m^2.)
Note 2: Unless otherwise explicity stated, it is to be understood that the sound pressure is the effective (rms) sound pressure
Note 3: It is to be noted that in many sound fields the sound pressure ratios are not the square roots of the corresponding power ratios.

Spectrum*

1. The spectrum of a function of time is a description of its resolution into components, each of different frequency and (usually) different amplitude and phase.
2. "Spectrum" is also used to signify a continuous range of components, usually wide in extent, within which waves have some specified common characteristic: e.g., audio-frequency spectrum."
Note 1. The term spectrum is also applied to functions of variables other than time, such as distance.

Transient Action Component

A mechanical device which, upon application of a given stimulus changes, from one stable state to another e.g. a solenoid valve.

Transducer*

A transducer is a device capable of being actuated by waves from one or more transmission systems or media and of supplying related waves to one or more other transmission systems or media.
Note: The waves in either input or output may be of the same or different types (e.g., mechanical, or acoustic).

Ultrasonics*

Ultrasonics is the technology of sound at frequencies above the audio range.
Note: Supersonics is the general subject covering phenomena associated with speed higher than the speed of sound (as in the case of aircraft and projectiles traveling faster than sound). This term was once used in acoustics synonomously with "ultrasonics;" such usage is now deprecated.

Velocity*

Velocity is a vector that specifies the time rate of change of displacement with respect to a reference frame.
Note: If the reference frame is not inertial, the velocity is often designated relative velocity.

Vibration*

Vibration is an oscillation wherein the quantity is a parameter that defines the motion of a mechanical system.

Vibration Isolator*

A vibration isolator is a resilient support that tends to isolate a system from steady-state excitation.

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*This material is reproduced from the American Standard Acoustical Terminology, S1.1-1960

ADDENDUM C

TEST PLAN
(Sample)
MECHANICAL SYSTEMS READINESS ASSESSMENT

AND

PERFORMANCE MONITORING STUDY

Structure Borne Acoustic Tests

Solenoid Valve 75M08825-3

December 17, 1971

TEST PLAN DB71-L043

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SECTION I

INTRODUCTION

1.1   PURPOSE

This test plan provides a description of hardware and procedures to be used in conducting structure borne acoustic tests of KSC Solenoid Valve 75M08825-3. Included in this plan are descriptions of component test set up, test flow and schedules, acoustic instrumentation and data reduction equipment, and detailed test procedures.

1.2   SCOPE

Components to be tested per this plan are three Solenoid Valves 75M08825-3. These components will be operated 30 times each with structure borne sound being recorded for each operation. Additionally, components will be modified to insert significant failure modes and actuated 30 additional operations for each failure mode. The recorded acoustic data will then be electronically reduced to permit establishment of valve readiness assessment limits.

1.3   TEST PROGRAM GROUND RULES

Ground rules include:

a.   Above components will be government finished equipment.

b.   All tests will be performed at General Electric, Schenectady, New York, Research and Development Center.

c.   All test equipment and instrumentation will be provided by GE.

1.4   APPLICABLE DOCUMENTS

In completing this test program, compliance will be maintained with the following documents:

a.   Contract NAS 10-7788, dated October 21, 1971

b.   NASA KSC Statement of Work for Study of Mechanical Systems Readiness
     Assessment and Performance Monitoring, dated July 7, 1971.

c.   GE Technical Proposal, Number 730214, dated July 30, 1971.

d.   GE Study Plan, Number DB71-J026, dated November 3, 1971.

e.   Marotta Valve Corporation Tech. Manual (MV74VE).

f.   KSC Technical Manual 440, June 28, 1968.

g.   Wilcoxon Research Instruction and Maintenance Manual 37-668.

h.   Honeywell Model 5600 Recorder Instruction Manual.

SECTION II

GENERAL

2.1   COMPONENT IDENTIFICATION

Solenoid Valve, 75M08825-3, is a three-way, two-position, normally open, magnetically
operated valve with a built-in electrical position indicator switch (see Figure 1).
Three of these components will receive 30 nominal operations each, these Valves
are Serial Numbers 202, 210, and 444. Component 202 will be modified to simulate
"fails to operate" and "sluggish operations" failure modes while Valve 210 will be
modified to simulate "erroneous indication" and leakage failure modes. After each
failure mode insertion the component will be actuated 30 additional operations.
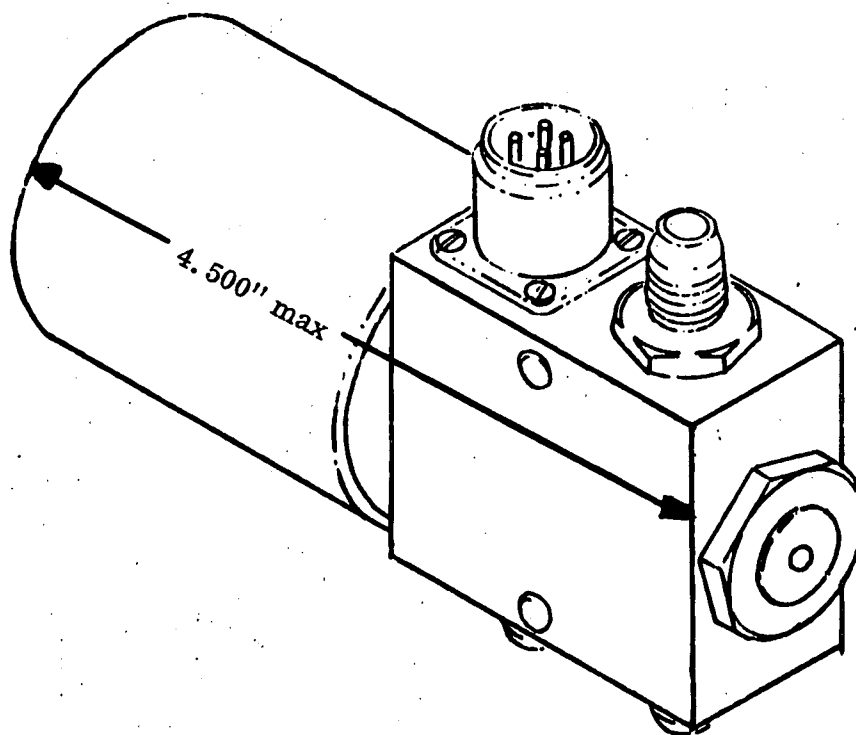
Figure 1
SOLENOID VALVE 75M08825-3

2.2 TEST SET-UP HARDWARE

Structure borne sound generated by Solenoid Valve 75M08825-3 will be monitored while the valve is being actuated in a normal operational environment. This environment will be simulated by the test set up illustrated in Figure 2 and 3. Hand Valve Number 2 will be closed throughout the valve test program. The KSC mechanical readiness test panel serves a dual purpose and HV_4, HV_5, HV_6, and G_2 will not be used in the performance of this test program. The detailed procedures for use of this test set up is presented in Section IV of this report and listing of equipment utilized is shown in Tables 1 and 2.

2.3 TEST FLOW

The actions which must be accomplished to complete this test program are shown as steps 1 through 21 in Figure 4, Solenoid Valve 75M08825-3, Structure Borne Acoustic Test Flow Diagram.

2.4 TEST SCHEDULE

Schedule for the major elements of this test program are depicted in Detailed Schedule, Figure 5. The test program will commence on or before December 27, 1971 and will be completed prior to February 11, 1972.

2.5 TEST DOCUMENTATION REQUIREMENTS

Sufficient documentation of test program will be provided to insure that test conditions and variables can be reproduced. The documentation will include proper recording of test parameters specified in Section IV detailed test procedures and sufficient records to deiine all test equipment, equipment interconnections, and test conditions of facility and hardware. Where possible, documentation of hardware already in existance will be utilized and referenced as required.

Panel made from 1/4" thick Al Stock.

GN_2 Source

HV_0

G_0

HV_1

G1
ACCO
Helico
Gauge
2491-0

HV_3

HV_2

75MD8825
Valve

GN_2 Bottle

HV_4

75MD8831

G3
Ashcroft
1056S

HV_7

HV_6

G2
Ashcroft
316

Vent

Vent

Vent

HV_5
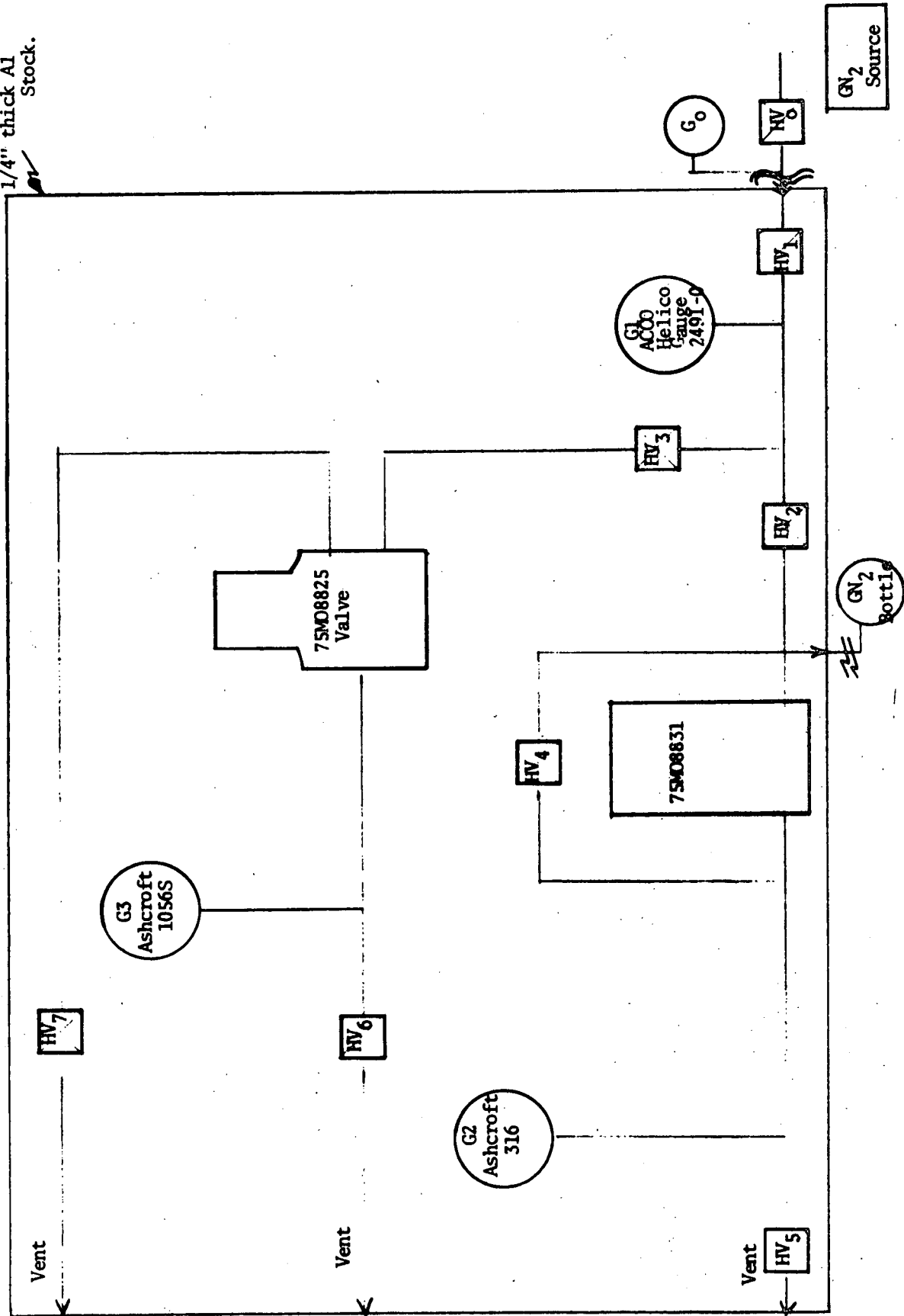
Figure 2
KSC MECHANICAL READINESS TEST PANEL
MECHANICAL CONNECTIONS

Dc-9
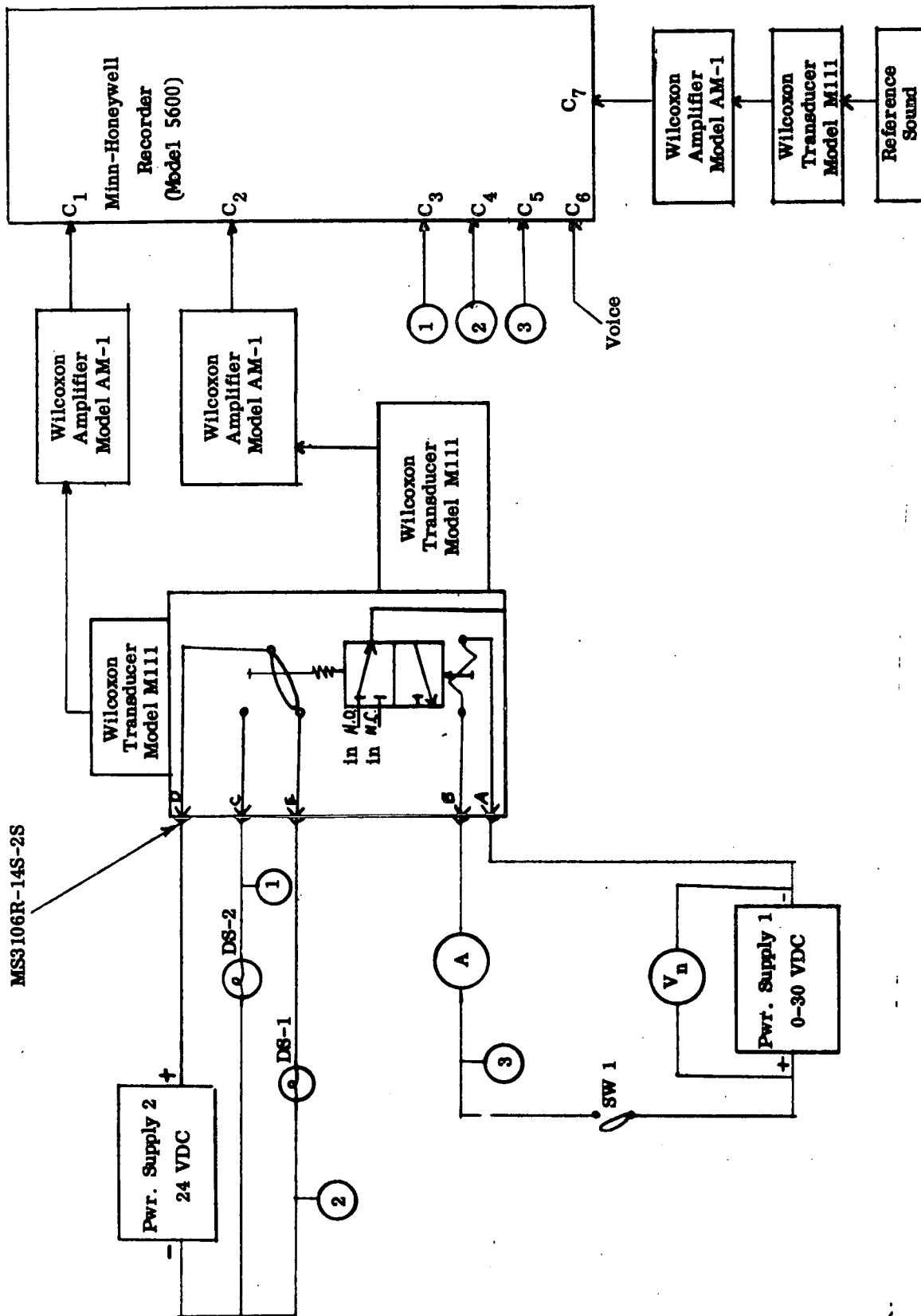
Figure 3. Mechanical Readiness Test Set Up
Solenoid Valve 75M08825-3 Electrical Connections

TABLE 1

MECHANICAL EQUIPMENT LIST

QUANTITY	ITEM	REMARKS
3	Test Specimen 75M08825-3	
1	Regulated Pressure Source	0-2500 PSIG Clean, Drg. GN_2, 10 Micron filtered - Air Reduction Co. or equivalent.
1	Gauge (G0) Matherson Co. 22025-1	0-3000 PSIG $\pm$ 1/2% full scale occurring
1	Gauge (G1) Acco Helco 2491-0	0-3000 PSIG $\pm$ 1/2% full scale occurring
1	Gauge G 3 Ashcroft 10565	0-3000 PSIG $\pm$ 1/2% full scale occurring
5	Hand Valves (HV_1, HV_2, HV_3, HV_6 and HV_7)	1/4", 3000 PSIG Serial HOK8 or equivalent.
AR	Tubing ASTM-A-213 Stainless Steel	3/8" OD - .035" Wall
AR	Connectors	As required to connect tubing and mechanical components specified in Figure 2.
1	Panel 2' x 4'3" x 1/4" Aluminum stock	

TABLE 2

ELECTRICAL EQUIPMENT LIST

QUANTITY	ITEM	REMARKS
3	Test Specimen 75M08825-3	GFE
1	Power Supply 2	24 + 6 VDC 1 Amp Max. Service
2	Lamps (DS 1 and DS 2)	28 VDC
3	Transducer, Piezoelectric	Wilcoxon M-III
3	Amplifier	Wilcoxon Model AM-1
1	Recorder, Data	Minn. Honeywell Model 5600 or equivalent
1	Ammeter	+ 5% accuracy
1	Voltmeter	Simpson 260 or equivalent
1	Power Supply 1	Variable 0-30 VDC 5 amp. max service
AR	Electrical Cables and Connectors	As required to interconnect circuitry specified in Figure 3.

Solenoid Valve 7SM08825-3

Figure 4. Structure Borne Acoustic Test Flow Diagram

FISCAL WEEK SCHEDULE

STRUCTURE BORNE ACOUSTIC
TEST PROGRAM-SOLENOID VALVE 7SM08825-3

Feb. 10, 1972

Task	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
• SELECT & SECURE ALL HARDWARE	▨																
• TEST SET-UP	▨																
• CHECKOUT TEST SYSTEM		▨															
• CONDUCT OPERATIONAL TEST & RECORD DATA			▨	▨													
• VERIFY ANALYTICAL DESCRIPTION				▨													
• ESTABLISH MEASUREMENT TECHNIQUES					▨												
• CALIBRATE & CHECKOUT DATA REDUCTION EQUIPMENT				▨													
• ACOUSTIC DATA REDUCTION					▨												
• DETERMINE ASSESSMENT LIMITS						▨											
• FAILURE MODE TEST (INSERT FAILURES A THROUGH D & REPEAT TEST & ASSESSMENT SEQUENCE)					▨	▨											
• FAILURE MODE MEASUREMENT TECHNIQUES & ASSESSMENT LIMIT							▨										

Figure 5. - DETAILED SCHEDULE, SOLENOID VALVE 7SM08825-3 TEST PROGRAM

SECTION III

TEST FACILITIES

Test facilities at General Electric's Research and Development Laboratory, Schenectady, New York will be employed for this test program. To acquire acoustic data, sufficient space in Room 1062 (approximately 80 ft^2) will be required. A work bench will be provided and proper tools will be available to tune and adjust electrical and mechanical networks shown in Figures 2 and 3. Facilities temperature range of $65^\circ \pm 5^\circ$ F, humidity range of $45 \pm 5\%$ and normal open laboratory cleanliness will be maintained.

Facility electrical power requirements are 115 volts AC with total current of less than 30 amp. Sufficient networks will be available to accommodate power supplies and recorders as shown in Figure 3. Normal laboratory lighting levels will be maintained.

SECTION IV

DETAILED TEST PROCEDURES

4.1 TEST SEQUENCE

The sequence for completing each step of this test program is shown diagramatically in Figure 5. The order involves, at first, the identification and accumulation of all electronic and mechanical hardware; Second, assembly and checkout of test set up, including the test component; Third, assembly and checkout of complete test systems including instrumentation; Fourth, test operations and recordings; Fifth, determine measurement technique; Sixth, assembly and checkout of data reduction equipment; Seventh, acoustic data reduction. Provisions must be made to recycle tests if later data analysis indicates selection of a different measurement technique or stabilization of a test variable will permit establishment of value assessment criteria.

4.2 TEST SET UP

The test panel previously shown in Figure 2 will be installed at test berth in Room 1062. 3000 PSIG GN_2 source will be connected to panel, as shown in Figure 2. All lines must be clean and connections will be bubble tight leak proof checked at 2500 PSIG GN_2. Sherlock type CG-1 leak test solution or equivalent will be used. Valve Serial #202 will be placed in test panel.

The test set up will be checked out in accordance with following detailed test procedure. Data will be recorded as for each step of valve checkout as defined on Test Recording Form (see Figure 6). Should problems be encountered during any step of this test; KSC TM-440, Failure Mode and Effect Analysis Drawing 65B23278-23, or Marotta Valve Corporation, Technical Manual Revision B for Model MV74VE should be referenced for appropriate corrective action.

FIGURE 6

75M08825-3 Solenoid Valve

Test Recordings

I. Valve Checkout Test

Step Number	T_1	DS1	G0	G1	G3	HV0	HV1	HV2	HV3	HV6	HV7	V_n	A	Source Pressure
1														
2														
3														
4														
5		Leak test Readjust valve or replace if not bubble tight												
6														
7		Leak test Readjust valve or replace if not bubble tight												
8		5 cycles of SW-1- Record actuation times T_1, DS_1, DS_2, V_n and A												
8_1														
8_2														
8_3														
8_4														
8_5														
9		Record voltage solenoid												
10														
11		Record voltage that solenoid energizes												
12														
9_1														
10_1														
11_1														
9_2														
10_2														
11_2														
9_3														
10_3														
13														
14														
15														

4.3   VALVE CHECKOUT TEST PROCEDURE

STEP	PROCEDURE	RESULT
	⬛ WARNING ◣	
	Solenoid valve must be secured behind a protective barrier for personnel protection when valve is pressurized.	
1	Prepare test setup in accordance with figure 2, with all hand valves closed.	
2	Adjust regulated pressure source to 2500 psig.	
3	Open hand valve,HV0,HV-1 & HV-3 Set power supplies 1 and 2 to 28 vdc.	Gages G-0, G-D and G-3 indicate 2500 psig. DS-1 illuminates DS-2 OFF. (See Figure 3)
4	Close HV-1 and open HV-7.	
5	Leak test valve (using leak test solution, Sherlock type CG-1).	Valve shall be bubble tight.
6	Close switch SW-1 (See Figure 3)	DS-1 OFF and DS-2 illuminates. G-3 indicates zero psig.

STEP	PROCEDURE	RESULT
7	Leak test valve.	Valve shall be bubble tight.
8	Cycle SW-1 five times. Allow 30 seconds in each position.	Valve must actuate and deactuate without hesitation.
9	Slowly decrease voltage on power supply 1 from 18 to 0 volts.	Solenoid denergizes above 1 vdc. DS-1 illuminates DS-2 OFF.
10	Adjust power supply to zero volts.	
11	Slowly increase voltage from 0 to 18 volts.	Solenoid energizes between 8 to 18 volts. DS-1 OFF DS-2 illuminates.
12	Repeat steps 9, 10 and 11 three times.	
13	Open SW-1.	DS-1 illuminates DS-2 OFF
14	Set power supply switch to OFF.	
15	Shut off pressure source and open HV-1, HV-3, HV-6 HV-7.	

4.4 ACOUSTIC INSTRUMENTATION

Wilcoxon Peizelectric Transducers Model M111 and Amplifier Model AM-1 will be calibrated in accordance with Wilcoxon Research Instruction and Maintenance Manual (Model AM-1) #37-668.

The transducers will be mounted on Solenoid Valve Housing (Part #36) at location shown in Figure 7. The transducer mounting surface is 1/4" diameter. The transducers will be cemented rigidly to the valve housing using either Eastman 910, EC-1294 (3M Company), Epon 828 (Shell), or Dental cement such as GRIP (L. D. Caulk Company). Eastman 910 may be removed with N-Dimethylformamide.

To prevent ground loops, both the amplifier and transducer must be insulated from ground with a single point ground being fed from the recorder input.

Honeywell Model 5600, 1 inch, 14 channel tape recorder will be used for magnetic recording of va ve structure borne acoustics. This recorder will be calibrated and o erated per Honeywell Model 5600 instruction manual. Data Channel to be recorded for each test are depicted in Figure 3 and include:

Channel 1 - Valve Accelerometer #1
Channel 2 - Valve Accelerometer #2
Channel 3 - Valve Switch Indicator #1
Channel 4 - Valve Switch Indicator #2
Channel 5 - Valve Solenoid energization voltage
Channel 6 - Voice Channel to identify test, tape speed, etc.
Channel 7 - Reference Accelerometer.
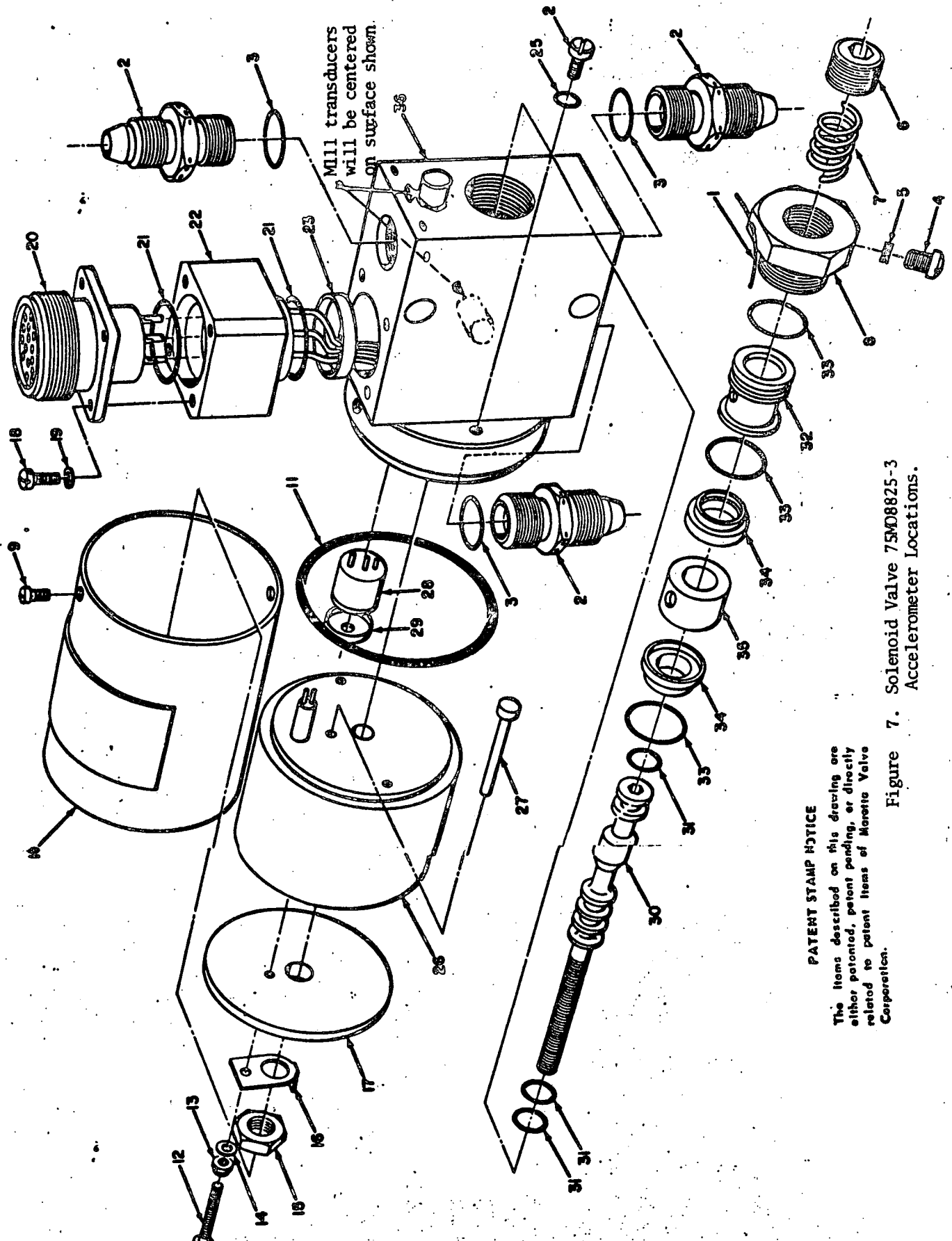
Mill transducers will be centered on surface shown.

Figure 7. Solenoid Valve 75M08825-3 Accelerometer Locations.

4.5   CHECKOUT TOTAL ACOUSTIC TEST SYSTEM

To insure the total test system is performing properly and that optimum gain settings are established for amplifiers, several operations of the Solenoid valve will be monitored. Steps 1 through 4 and step 6 of Valve Checkout Procedure (paragraph 4.3) will be followed. The seven channels of data specified in paragraph 4.4 will be recorded and played back or displayed to ascertain the performance of overall test system. SW-1 should be cycled and resultant outputs recorded until overall operation of test system is satisfactorily verified.

4.6   CONDUCT ACOUSTIC TEST AND DATA RECORDING

The nominal oeprating time for Solenoid Valve 75M08825-3 is approximately 25 milliseconds to actuate and 5 milliseconds to deactuate. With the test circuitry previously described still in place, Steps 1 through 4 and Step 6 of valve checkout procedure (paragraph 4.3) will be repeated. All electrical equipment should be brought to the power-up mode of operation, and tape recorder set in record mode. Data, Valve identification, nominal operating conditions, and length of test should be read in on recorder voice channel. SW-1 should then be cycled 30 operations. Sound data will be recorded a minimum of 150 milliseconds after solenoid energization and 50 milliseconds after deactuation. The time element between cycles should all be minimized to aid in subsequent data reduction task. Throughout test G1 and G3 should be monitored to verify that valve is switching correct pressure levels. Any deviation of GN_2 pressure will be recorded.

Dc-22

Subsequent to above test, Steps 13, 14, and 15 of valve checkout procedure will be accomplished and all electrical equipment switched to Power Off mode.

Next, Solenoid Valve 75M08825-3, Serial #210, will be placed in test panel (Figure 2) and complete sequence of tests described above will be repeated.

Then, Solenoid Valve 75M08825-3, Serial #444, will be placed in test panel (Figure 2) and once agains the complete sequence of tests repeated.

Solenoid Valve 75M08825-3, Serial #202, will have failure Mode A - fails to operate - inserted and will be mounted into the test panel and complete sequence of tests repeated.

Solenoid Valve 75M08825-3, Serial #210, will have failure Mode B - erroneous indication - inserted and will be mounted into the test panel and complete sequence of tests repeated.

Solenoid Valve 75M08825-3, Serial #202, will have failure Mode C - leakage - inserted and will be mounted into the test panel and complete sequence of tests repeated.

Solenoid Valve 75M08825-3, Serial #210, will have failure Mode D - sluggish operation - inserted and will be mounted into the test panel and complete sequence of tests repeated.

4.7 MEASUREMENT TECHNIQUES

It is impractical to attempt to predefine the precise measurement techniques
or variations of basic techniques which might be the most advantageous for
ultimately establishing valve 75M08825-3 assessment limits that can discriminate
between GO, NO-GO, and CAUTION conditions. However, the approach to be pursued
will include the following techniques. Step 1 will consist of an overall (narrow
band) Spectral Analysis presentation of 210 total valve operations. The GE
Research and Development Laboratory Spectrum Pattern Analysis facility, Room 5036,
will be used to present this data. Functions of the facility
include the generation of spectra; recording of spectrum patterns on 35 mm film
spectrograms; local minicomputer processing of spectra; and the recording of
waveforms and spectra on digital magnetic tape for processing in a large G.E. 600
series computer system. Facility equipment includes analog magnetic tape recorders,
two complementary real-time frequency analyzers, a 622/i Varian Minicomputer
equipped with automatic analog to digital and digital to analog input and out-
put systems, a digital magnetic tape recorder, display format generating and
control circuits, display units, a 35 mm film recording camera, and an automatic
film processor. In addition, specially designed interface units are available
to speed data processing.

Twenty percent of Spectrum (every 5th operation) displayed will be recorded directly on film as a continuous time series of amplitude versus frequency plots. The remainder of operations will be operated on to create intensity modulated spectrograms. No more than 10 operations will be displayed on a single 8-1/2 x 11 sheet.

Based on visual observation of relationship of Spectra distinctive features with predicted acoustic signatures and the mechanics of solenoid valve operation, additional measurement techniques will be investigated.

It is anticipated that discrete band pass filtering will enable the investigation to reduce the volume of analogue data requiring further manipulation. Various filters are available in Mechanical Signature Analysis Laboratory - Room 603 - which may be used in this process are:

(1) Band Pass Filter 1/3 octave/octave
      Bruel and Kjar Type 1612.

(2) Variable filter 20 cps-200 KC
      Krohn Hite Model 315AR.

(3) Filter
      Krohn Hite Model 3340R.

The filter chosen will be dependent on frequency band selection. The Signature in reduced form will then be processed to detect transient occurrence of peak levels, Peak/Time relationship comparison, Number of Peaks during Valve operating cycle RMS level and Peak level vs. RMS level crest factors. Equipment which will be used to detect these Peak and RMS level characteristics are:

(1) Hewlett Packard 5480B Memory Scope with
      HP5486B control and 5488A.

(2) Honeywell Strip Recorder

(3)   Valentine Peak to Peak Voltmeter.

(4)   Textronix Type 561A Oscilloscope.

(5)   Dymac 2401C Integrating Digital Voltmeter.

(6)   Hewlett-Packard 2401C Integrating Digital Voltmeter.

Auto correlation processing will be accomplished to detect significant internal waveform relationships. Failure mode waveforms will be cross correlated against normal (idealized) operation waveform. The idealized waveform will be shifted in time relative to the actual failure mode waveforms, and when the correlation function is a maximum, the positions of noise bursts will be located. The correlation technique will then look between the noise peaks to determine signal amplitude in what is normally a quiet period, measure the amplitude of the existing noise bursts, identify the largest of them, determine the average amplitude of the predominate noise bursts, and then take various ratios between these measured valves. These measurements and ratios will be compared to nominal operation valves. Principle Correlation equipment to be used is:

(1)   Honeywell 9410 Correlator.

(2)   Princeton Applied Research Correlator

(3)   Hewlett-Packard 5488A Average/Correlator.

Completion of the above data procsssing and reduction will terminate tests until data in the specified form has been statistically evaluated and assessment limits established.

4.8   TEST RECYCLING

Should evaluation of test data show that uncontrolled test variables, faulty instrumentation, or data reduction problems, invalidate data and limit conclusions that can be drawn to the extent that assessment limits cannot be established, the problem will be corrected and test recycled.

ADDENDUM D

PIEZOELECTRIC ACCELEROMETERS *

ACCELERATION TRANSDUCERS

A piezoelectric accelerometer is an instrument used to measure shock and vibration. It can be idealized by a mass element connected to the case by a spring and a damping medium. The transducing element produces an electrical output proportional to the displacement of the mass element relative to the case and also proportional to the acceleration applied to the case. Most accelerometers can be represented as a single-degree-of-freedom system and are sensitive only in one axis.

The sensitivity of an accelerometer is the ratio of its electrical output to applied acceleration, usually expressed as picocoulombs/g or Volts/g. It is constant at all frequencies up to approximately one-fifth the resonant frequency.

PIEZOELECTRIC MATERIALS

A piezoelectric material is one which generates an electrical charge when subjected to a mechanical stress or deformation. As a self-generating sensing material, it usually produces a large output for its size, and is useful to extremely high frequencies. Rochelle salt, tourmaline, and quartz are examples of "natural" or single crystal piezoelectric materials used in some applications, but ferroelectric ceramics are used in most piezoelectric accelerometers.

Certain ferroelectric substances can be made to exhibit piezoelectricity by a process of artificial polarization. These polycrystalline ceramics include barium titanate, lead zirconate, lead titanate, and lead mentaniobate. The great importance of the ferroelectric materials is that their piezoelectric properties can be controlled in the manufacturing process to produce the characteristics necessary to make a good accelerometer.

ACCELEROMETER DESIGN

Several designs of accelerometers are illustrated in Figure A. The inertial mass is identified with the letter M, and the ceramic crystal, shown between the mass and support and acting as a stiff spring, by the letter K. The letter K with various subscripts also identifies case walls or other members which act as springs in the accelerometer.

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*The majority of data and all figures contained in this Appendix
are excerpted from the Endevco Corporation Instruction Manual (#101),
(Courtesy Endevco Corporation).

Dd-1
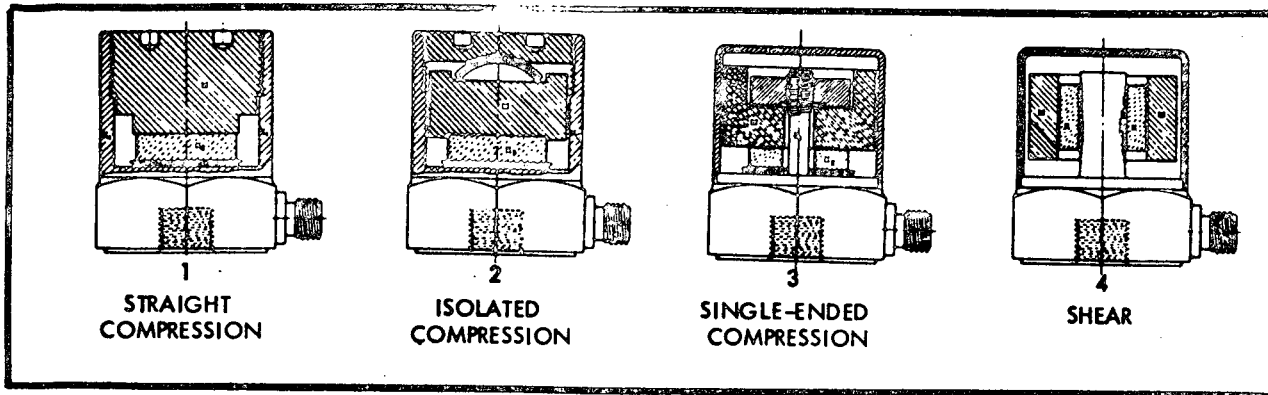
FIGURE A

Accelerometer Designs

The shear design has several unique advantages. As in single-ended compre-
ssion design, the case acts only as a protective cover and is not in contact
with the spring-mass system. Also, if the center post is made hollow and
extended through the case, the resulting accelerometer can be mounted by
simply passing an ordinary machine screw through the hole to attach it to
the test structure. Another major advantage of the shear approach is that
it can quite successfully be built with extremely small dimensions. The
majority of light-weight microminiature accelerometers are shear units.

PIEZOELECTRIC ACCELEROMETER CHARACTERISTICS
EQUIVALENT CIRCUITS

The equivalent circuit for a piezoelectric transducer is shown in Figure 1. In practice, the
internal resistance shown in circuit (A) normally exceeds 20,000 megohms and, thus, can be
ignored when considering the over-all transducer performance. Similarly, effects due to the
internal inductance are far beyond the upper frequency limit of the transducer and can also
be ignored. The simplified circuit (Fig. 1B) is adequate for applications analysis. The pie-
zoelectric transducer is effectively a capacitor which produces a charge ,q, across its plates
proportional to a force applied to the crystal.

The open circuit voltage ,e, out of the transducer is equal to the generated charge divided by
the transducer capacitance, or $e \text{ (Volts)} = \frac{q \text{ (picocoulombs)}}{C_p \text{ (picofarads)}}$. Thus, the transducer can also
be represented as a voltage generator and a series capacitance (Fig. 1C).

Dd-2
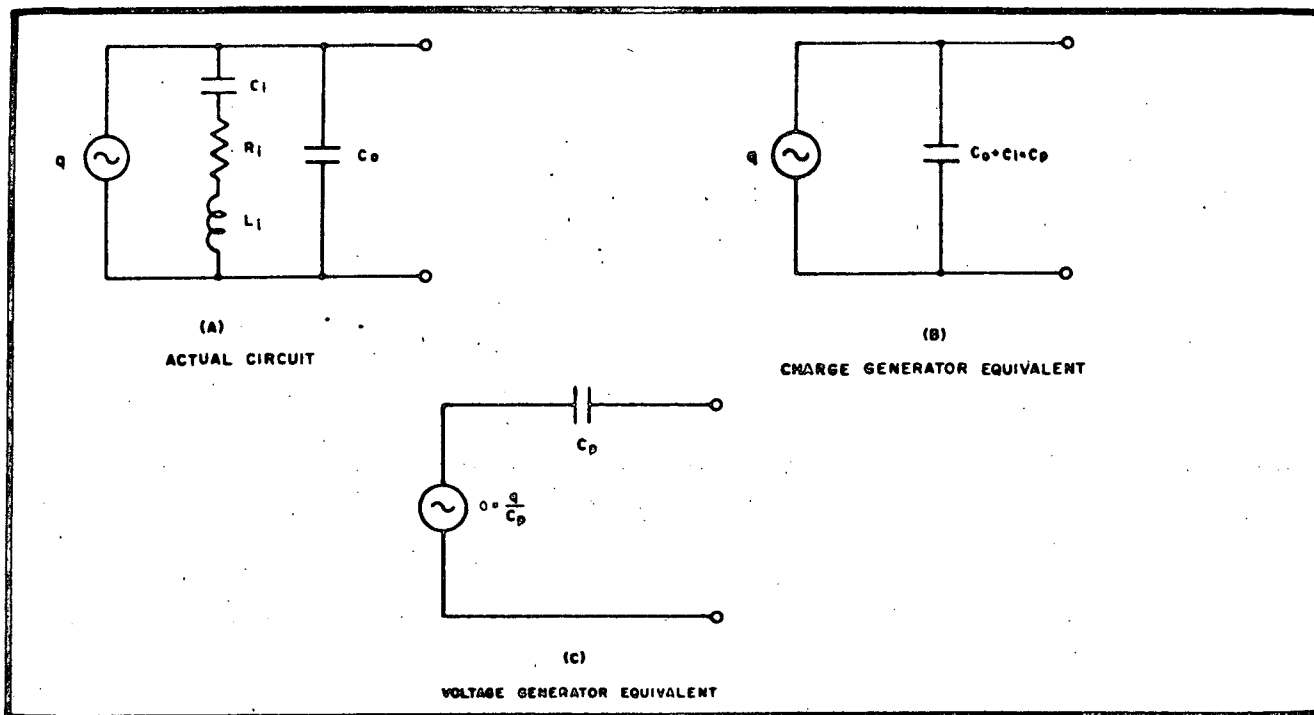
FIGURE 1.

Equivalent circuits for a piezoelectric transducer (A)actual circuit,
(B) charge generator equivalent, and (C)voltage generator equivalent.

SENSITIVITY

The sensitivity of an accelerometer is defined as the ratio of its electrical output to its mechanical input. It may be expressed in units of charge per unit of acceleration or voltage per unit of acceleration. It is important to note the terms in which the respective parameters are expressed; e.g., average, rms or peak.

Charge Sensitivity

Each accelerometer is provided with a charge sensitivity calibration, Q, expressed in picocoulombs per g (pC/g). This is measured directly or derived from Q=EC, where Q is expressed in picocoulombs, E in Volts, and C in pico-farads. This calibration is used when the accelerometer is operating into charge measuring electronics. Note that magnitude of sensitivity can be expressed in other terms:

$$\frac{pC}{g} = \frac{rms\ pC}{rms\ g} = \frac{pk\ pC}{pk\ g}$$

Voltage Sensitivity

Each calibration card also carries the accelerometer voltage sensitivity, E, in millivolts per g (mV/g) as measured with a stated amount of external capacitance connected to the accelerometer. Use the value 0.707 x E rms mV/pk g when observing the signal level on an rms VTVM. Use 2 x E as the accelerometer sensitivity when measuring peak-to-peak voltages with a galvanometer recorder or oscilloscope.

Effect of Cables on Sensitivity

When performing measurements, the transducer circuit involves an external capacitance and a shunt resistance. The external capacitance C_t is commonly cable capacitance plus input capacitance of the associated amplifier. The shunt resistance R_i is commonly the input resistance of the associated amplifier (Fig. 2).
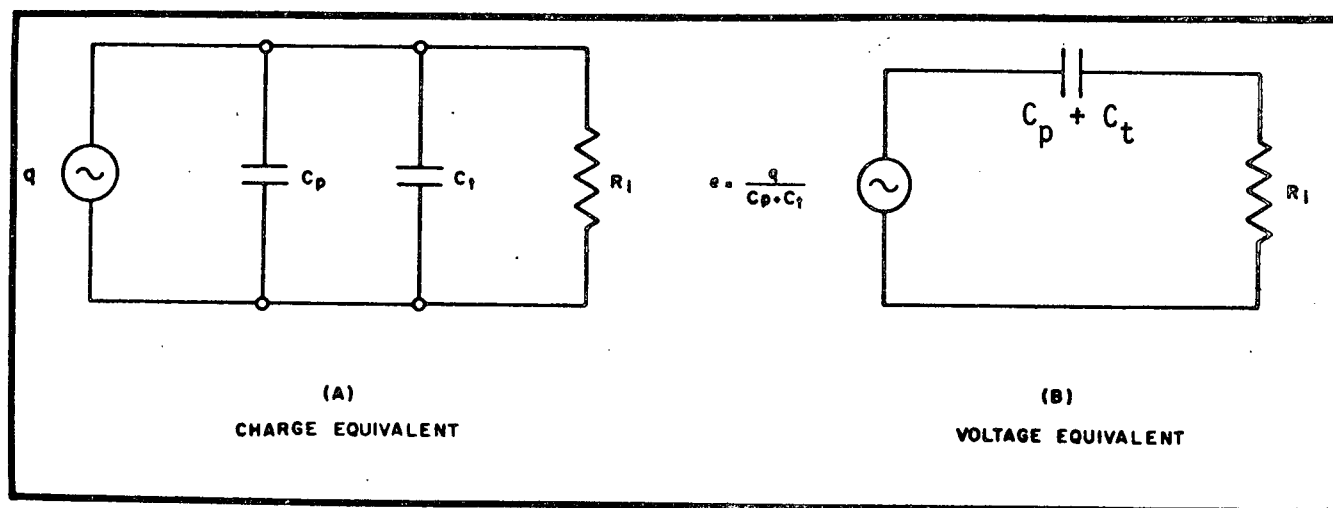
FIGURE 2.

Equivalent circuits for a normal piezoelectric transducer system
(A) charge equivalent and (B) voltage equivalent.

Since the charge generated does not change, regardless of the amount of external capacitance added, the charge sensitivity of the accelerometer remains uneffected by the length of interconnecting cable. This characteristic explains the practical advantage of a system incorporating charge measuring electronics rather than voltage amplifiers.

When using voltage amplifiers the amount of external capacitance must be considered in establishing the signal at the input of the amplifier. With added capacitance the output voltage (appearing across R_i) becomes $e = \dfrac{q}{C_p + C_t}$.

The total system capacitance during actual use may differ from the capacitance that was used in the original calibration. This changes the basic voltage sensitivity up or down by a calculable amount. The new sensitivity can be determined with either of two equations:

$$1. \qquad E = \frac{Q}{C_p + C_t} \times 1000 \text{ mV/g} \qquad (1)$$

E = new sensitivity being determined, in millivolts per g (mV/g).

Q = factory supplied charge sensitivity, in picocoulombs per g (pC/g).

C_p = transducer internal capacitance, in picofarads (pF).

C_t = total capacitance external to the transducer for which E is being established, in picofarads (pF).

For example:

Q = 34.7 pC/g

C_p = 575 pF

C_t = C_{cable} (200 pF) = C_{ampl} (25 pF)

     = 225 pF

E = $\dfrac{34.7}{575 + 225} = \dfrac{34.7 \times 10^{-12}}{800 \times 10^{-12}}$ = .0434 Volts/g

E = 43.4 mV/g = 43.4 pk mV/pk g

$$2. \qquad E = E_{cal} \frac{C_p + C_{cal}}{C_p + C_t} \qquad (2)$$

Where

E = new sensitivity being determined, in mV/g.

E_{cal} = factory supplied voltage sensitivity, in mV/g.

C_p = transducer internal capacitance, in pF.

C_{cal} = external capacitance used when calibrated at factory, in pF.

C_t = total capacitance external to the transducer for which E is being established, in picofarads (pF).

For example:

$$E_{cal} = 51.4 \, mV/g.$$

$$C_p = 575 \, pF.$$

$$C_{cal} = 100 \, pF.$$

$$C_t = C_{cable} \, (200 \, pF) + C_{ampl} \, (25 \, pF).$$

$$= 225 \, pF.$$

$$E = 51.4 \frac{575 + 100}{575 + 225} = 51.4 \frac{675}{800} = 43.4$$

$$E = 43.4 \, mV/g.$$

Note: (a) The values for Q, C_p, E_{cal} and C_{cal} will be found on the individual calibration cards shipped with each transducer.

(b) The residual capacitance of many voltage amplifiers is approximately 25 pF. Consult individual amplifier data sheets.

(c) E and E_{cal} may be expressed as either rms mV/pk g or pk mV/pkg, where: mV/g = rms mV/rms g = pk mV/pk g and rms mV/pk g = .707 mV/g.

Standardization - Voltage Sensitivity

The effect of added shunt capacitance on voltage sensitivity can be used to advantage in standardizing accelerometer output to a desired value.

Shielded capacitors can be used to standardize the sensitivity of any accelerometer to any value E less than its original calibration E_{cal} such as 10 ms mV/ pkg, so that g levels instead of millivolts can be read directly from the scale of a vacuum tube voltmeter without interpolation. In other instances where very high g levels are expected, it may be necessary to reduce the sensitivity of the accelerometer by a factor of 10 or more in order not to exceed the 5-volt output limit of most voltage amplifiers. To arrive at the exact capacitance

to be added to an accelerometer for a desired value of E, use Equation 1
above in this new form:

$$C_t = \frac{Q}{E} - C_p \qquad (3)$$

For example:

E = 10 pk mV/pk g (desired value)

Q = 34.7 pk pC/pk g

C_p = 575 pF

$$C_t = \frac{34.7 \times 10^{-12}}{10 \times 10^{-3}} \quad 575 = (3470 - 575) \times 10^{-12}$$

C_t = · 2895 pF.

Alternatively, we may use a new form of Equation 2:

$$C_t = \frac{E_{cal}}{E} (C_p + C_{cal}) - C_p \qquad (4)$$

For example:

E = 10 pk mV/pk g (desired value)

E_{cal} = 51.4 pk mV/pk g

C_p = 575 pF

C_{cal} = 100 pF

C_t = $\frac{51.4}{10}$ (575 + 100) - 575

= 5.14 (675) = 575

= 3470 - 575

C_t = 2895 pF
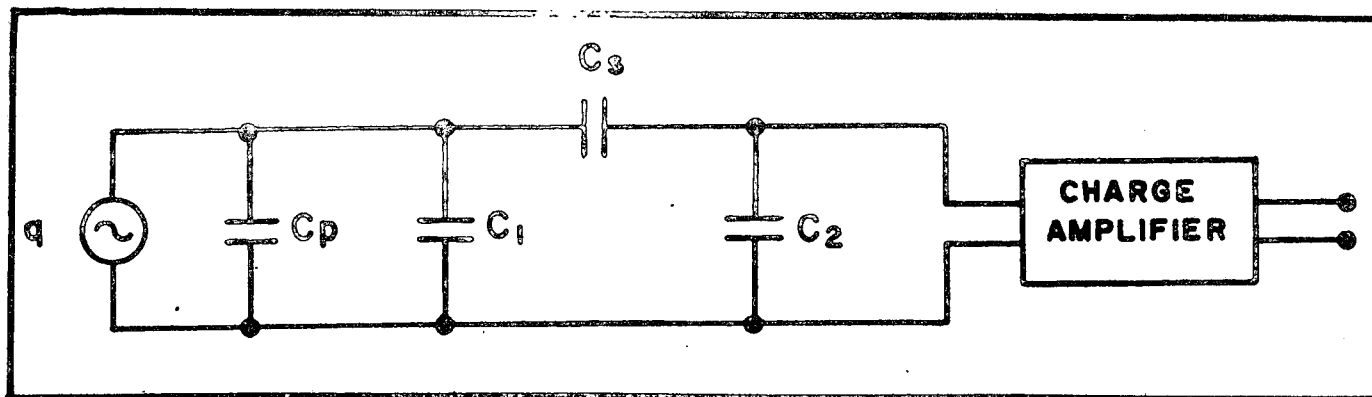
FIGURE 3.

Series swamping equivalent circuit - for reducing transducer charge output.

Standardization - Charge Sensitivity

Although adding shunt capacitance has no effect, addition of series capacitance will reduce the effective transducer charge output. See Figure 3. The charge which appears at the charge amplifier input is:

$$Q_{amp} = Q \frac{C_s}{C_p + C_1 + C_s} \tag{5}$$

Where ,

Q = basic transducer charge sensitivity, in pC/g.

C_p = transducer internal capacitance, pF.

C_1 = external parallel capacitance ahead of series capacitor, pF.

C_s = series swamping capacitance. pF.

C_2 = external parallel capacitance beyond the series capacitor, pF.

Note that although C_2 is, in general, present, it has no effect on system charge sensitivity.

FREQUENCY RESPONSE

Low Frequency Response

A piezoelectric accelerometer is a self-generating transducer that produces an electrical output signal that is proportional to acceleration, without the use of an external power source or carrier voltage. In practice, such a transducer cannot be used to measure constant or steady-state accelerations. At zero frequency no mechanical energy is being put into the system, thus electrical energy cannot be continuously removed.

When using charge amplifiers the system low frequency response is determined primarily by the low frequency response of the amplifier. The length of cable between transducer and amplifier will not affect the low frequency of the system, which is limited only by the characteristics of the amplifier.

Dd-8

When using voltage amplifiers, the low frequency response of a piezoelectric accelerometer is a function of the RC time constant of the accelerometer and the input resistance of the matching electronics.
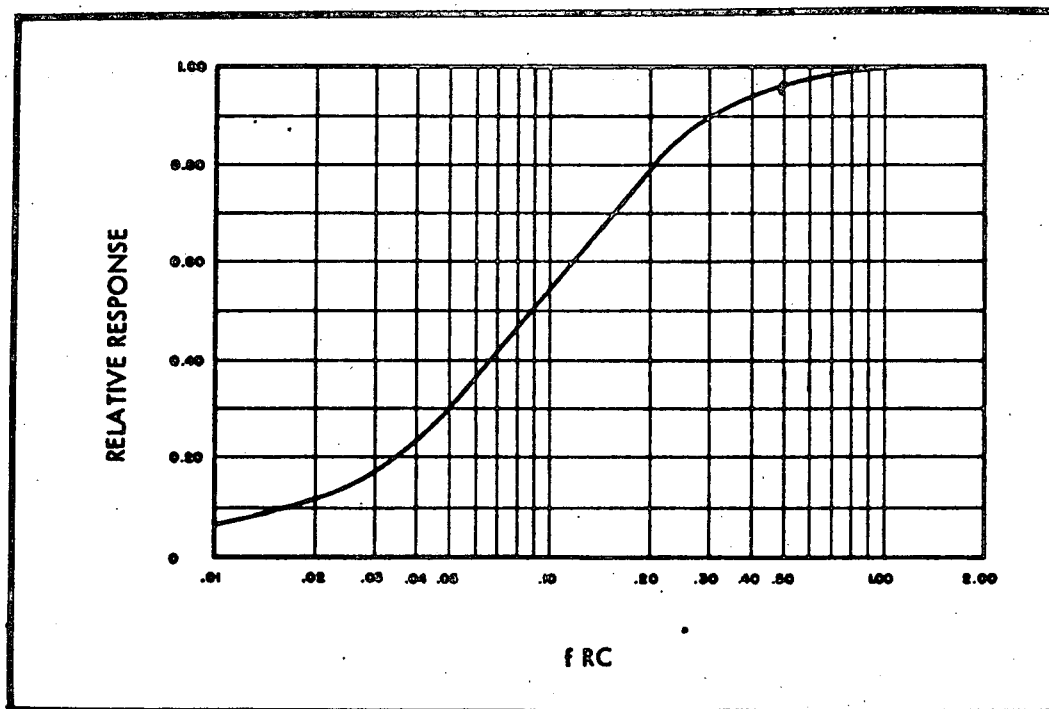
FIGURE 4.

Low frequency response vs. loading (voltage amplifiers).

The low frequency response of any accelerometer can be improved by swamping with additional shunt capacitance, such as long cables, to raise the RC time constant. However, this technique will also affect sensitivity as discussed on the preceeding pages.

Actual response at any frequency can be measured from Figure 4:

Where

f = frequency in Hz

R = input resistance of the matching amplifier in Ohms

C = total capacitance in farads of the accelerometer, plus additional applied shunt capacitance, if any

Example:

If frequency (f) of desired measurements if 10 Hz, total capacitance (C) of accelerometer and cable is 500 pF, and amplifier input impedance (R) is 100 MΩ (Endevco® cathode follower), we can determine:

$$f \times R \times C = 10 \times 100 \times 10^6 \times 500 \times 10^{-12} = 0.50$$

Using Figure 4, we find that the relative response corresponding the fRC = 0.5 is 95% (indicating that the signal at 10 Hz will be down approximately 5%).

Using the same formula in the case of a Model 2215E Accelerometer with an approximate capacitance of 9,500 pF we can see that for frequency response to 10 Hz and 10 MΩ input impedance, we obtain:

$$f \times R \times C = 10 \times 10 \times 10^6 \times 9,500 \times 10^{-12} = 0.95$$

Again using Figure 4, the relative response is approximately 99%. Thus, a 10 Hz signal will be down approximately 1%.

High Frequency Response

High frequency response of a piezoelectric accelerometer is a function of its mechanical characteristics. A piezoelectric accelerometer can be represented as a single-degree-of-freedom spring-mass system, the response of which is shown in Figure 5 as a function of frequency.
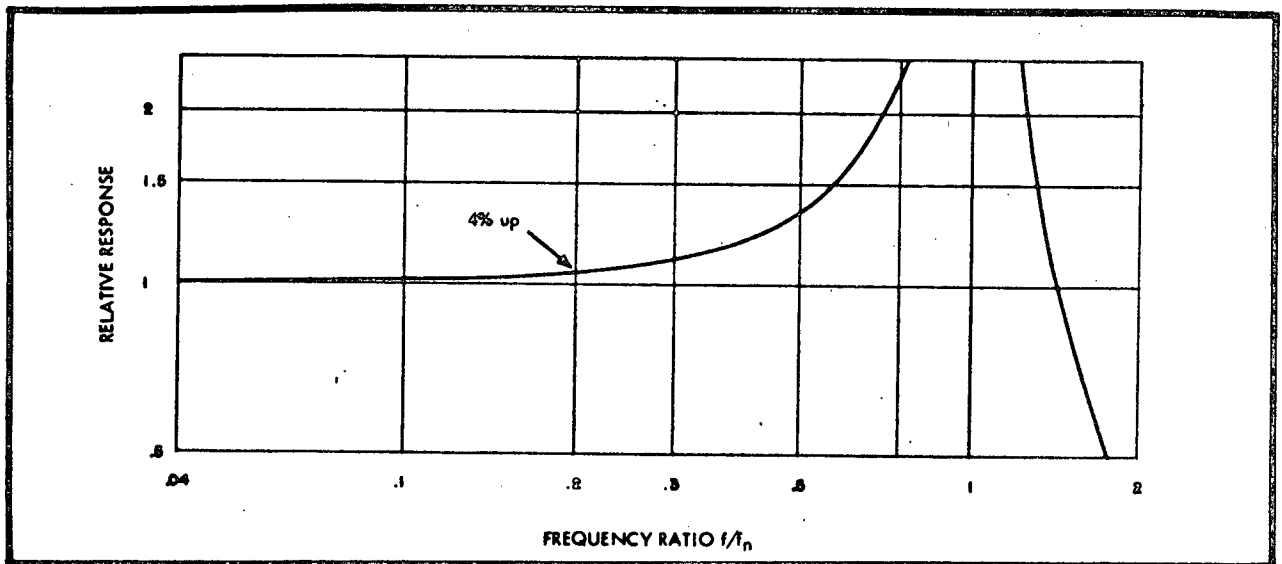
FIGURE 5.

Response of a single-degree-of-freedom spring-mass transducer when the case is undergoing sinusoidal acceleration.

For the accelerometer, this curve can be considered as showing the variation in sensitivity of the transducer with frequency. The response curve shows that at 1/5 the resonant frequency, the response of the system is 1.04. This means that the sensitivity of the accelerometer is 4% higher at that frequency than at the lower frequencies. For this reason the "flat" accelerometer frequency range should be considered limited to 1/5 the resonant frequency. Data can, of course, be obtained for frequencies above 1/5 the resonant frequency, as long as appropriate correction factors are applied to compensate for the "resonant rise".

Resonant Frequency

The USA Standards Institute defines resonant frequency as that frequency at which the sensitivity of the pickup is a maximum. Several methods are currently used to determine accelerometer resonant frequency.

Accelerometers should be selected with resonant frequencies at least 5 times higher than the highest frequency of interest (or with a natural period less than 1/5 that of an input shock pulse duration). To be valid, however, the resonant frequency specified must be mounted mechanical resonance.

Since the accelerometer will be mounted in use, the mounted resonance is the only one of value to the user.

DYNAMIC RANGE AND LINEARITY

The range of input acceleration levels for which accelerometer sensitivity remains constant is defined as the range of "Amplitude Linearity." Although a piezoelectric accelerometer is theoretically linear down to 0 "g", a practical lower limitation is imposed by the noise level of impedance matching electronics. For very low vibration levels, a high output accelerometer is required.

Upper limits of linearity may be imposed by either non-linear response of the piezoelectric element or by fragility of the transducer as a whole. In either case, the limits can be accurately determined only through actual evaluation. The sensitivity of all piezoelectric accelerometers increases with acceleration level.

PHASE SHIFT

In an accelerometer, phase shift is defined as the time delay between the mechanical input and the resulting electrical output signal. All vibration encountered in practice is complex, and like shock, is composed of a number of frequencies superimposed in a specific way. If transducer phase shift is not linear with frequency, the various frequency components will be shifted relative to one another and the resultant electrical output will be a distortion of the mechanical input.

Acoustic Noise

Considerable vibration in flight or static testing is induced by acoustical energy. It has been shown in numerous cases that random acoustical energy at 120 db can induce vibrations of the order of 50 g's or higher in structural members, and it can be assumed that higher acoustic levels may increase the vibration levels although not necessarily linearly. It has also been shown

that crystal accelerometers have, at the most, noise outputs equal to only a fraction of a g at 140 db noise levels so that if the usual high level vibrations are to be measured in acoustic fields, good signal-to-noise ratios and accuracies are obtainable. There are other cases, however, where low level evaluations on structures that are not subject to acoustic excitation must be made in high level acoustic fields. In these cases considerable attention must be paid to the acoustic response of the measuring system to assure good signal-to-noise levels and accuracies. The resonant frequency (f_n) of the crystal accelerometer must be at least three times the highest acoustic frequency expected.

RF and Magnetic Fields

Magnetic and RF fields have no effect on most piezoelectric elements. If an accelerometer includes magnetic materials a spurious output may be observed when it is vibrated in a high magnetic field or subjected to high intensity changing magnetic flux. Adequate isolation must be provided against RF ground-loops and stray signal pickup.

Temperature

In general, Endevco® accelerometers are rated for three temperature ranges: -65°F to +230°F, -65°F to +350°F, and -320°F to +500°F. In addition, Piezite® Element Type P-10 operates from -452°F to +750°F and is the only material that will cover these temperature extremes with good stability and large output. Within their usable temperature ranges, the various crystal materials show variations in sensivitiy, capacitance, and resistance. The deviation of voltage output with temperature is almost always different than the charge output deviation. It is, therefore, important when using charge measuring electronics to select accelerometers with flat charge characteristics, and with voltage equipment to choose accelerometers with flat voltage response curves.

As the accelerometer temperature is increased beyond its rated operating limit, the crystal begins to depolarize, with a resultant loss of sensitivity. If the unit is exposed to excess temperatures for only a short period, it may still be usable. It must, however, be recalibrated since it will have a new sensitivity of lower value. If the temperature is increased until the crystal reaches its Curie point, the accelerometer will be completely depolarized and unusable.

It was mentioned earlier that accelerometer low frequency response is dependent on the accelerometer-amplifier RC time constant (for voltage amplifiers). At higher temperatures, the internal resistance of piezoelectric crystals decreases, causing a reduction in the effective RC time constant. It is, therefore, very important to use accelerometers whose internal resistance remains high in high temperature applications.

At the very least, internal resistance as a function of temperature should be measured during calibration so that correction factors can be applied, if necessary.

ADDENDUM E

STRUCTURE BORNE ACOUSTICS HARDWARE MANUFACTURERS

The following listed vendors comprise only a representative sample of SBA hardware manufacturers. No endorsement is implied by the presence or absence of the hundreds of well-qualified vendors of the major equipment categories included within.

Accelerometers

Columbia Research Labs., Inc.
Conrac Corporation, Instruments and Control Division
Endevco, Dynamic Instrument Division
Kaman Nuclear, Division of Kaman Sciences Corporation
Kistler Instrument Company
Statham Instruments, Inc.
Systron-Donner Corporation, Inertial Division
Teledyne Inc., Automated Specialties Division
Wilcoxon Research

Amplifiers, Instrumentation

Where possible it is recommended that instrumentation amplifiers be procured from the accelerometer vendor. This assures a match of transducer and amplifier characteristics.

Analyzers, Vibration

B and K Instruments, Inc.
Bell and Howell, Electronics and Instruments Group
Chrysler Corporation, Huntsville Division
General Electric Company
General Radio Company
Hamilton Standard Division, United Aircraft
Hewlett-Packard
Honeywell Inc., Test Instruments Division
Hughes Aircraft Company, Space and Communications Group
Kaman Aerospace Corporation
Ling Electronics Division, LTV Ling Altec, Inc.
Polarad Electronics Instruments
Signal Analysis Industries Corporation
Tektronix, Inc.
Vibration Instruments Company
Wavelabs Company, Division of Systron-Donner Corporation
Weston Instruments

Cabling

Cabling for structure borne acoustics implementation is, in general, expected to be non-standard and fabricated to order.

Cabling between accelerometers and associated signal conditioning amplifiers ordinarily be procured from the vendor supplying these items.

Computers, Digital

Arma Division, AMBAC Industries, Inc.
Avco Corporation, Electronics Division
Bunker Ramo Corporation, Electronic Systems Division

EMR Computer Digital Equipment Corporation
Electronic Associates
Friden Division, The Singer Company
General Electric Company
Hazeltine Corporation
Hewlett-Packard
Honeywell Information Systems
International Business Machines Corporation
Lear Siegler, Inc., Electronic Instrumentation Division
Leeds and Northrup Company
Link Division, the Singer Company
Lockheed Aircraft Corporation
Melpar, Division of LTV Electrosystems Corporation
Mincom Division, 3M Company
Motorola/Government Electronics Division
National Cash Register Company
Northrup Corporation
Philco-Ford, Aerospace and Defense Systems Operations
RCA
Radiation Inc., Subsidiary of Harris-Intertype Corporation
Raytheon Company
Systems Engineering Laboratories, Inc.
TRW Systems Group
Teledyne Brown Engineering
Texas Instruments, Inc.
Univac Defense Systems Division, Sperry Rand
Wang Laboratories
Westinghouse Electric Corporation, Computer and Instrumentation Division
Weston Components Division, Weston Instruments, Inc.
Wyle Laboratories
Xerox Data Systems

Correlators

Hewlett-Packard
Signal Analysis Industries Corporation

Filters, Electronic

Analog Devices, Inc.
B and K Instruments, Inc.
Bendix Corporation, Electrical Components Division

Collins Radio Company
General Electric Company
General Instrument Corporation
General Radio Company
Hewlett-Packard
Sanders Associates, Inc.
TRW Electronic Functions Division
Teledyne Philbrick
Varian Associates
Vibration Instruments Company

Oscilloscopes

Automation Industries, Inc.
B and F Instrument, Inc.
B and K Division, Dynascan Corporation
Beckman Instruments, Inc.
Hewlett-Packard
Hickok Electrical Instrument Company
Honeywell, Inc., Test Instruments Division
International Telephone and Telgraph Corporation
Magnavox Company, Government Electronics Division
Monsanto Company
RCA, Electronic Components
Simpson Electric Company
Statham Instruments, Inc.
Tektronix, Inc.

Plotters, Data

Bendix Corporation, Environmental Science Division
Thomas A. Edison Industries, Instrument Division
Esterline Angus, Division of Esterline Corporation
Gerber Scientific Instrument Company
Hewlett-Packard
Houston Instrument, Division of Bausch and Lomb
Hughes Aircraft Company, Aerospace Group
Leeds and Northrup Company
Milgo Electronic Corporation
Potter Instrument Company, Inc.
RCA
Resdel Engineering Corporation
Scientific-Atlanta, Inc.
Teledyne Systems Company, Division of Teledyne, Inc.
Texas Instruments, Inc., Digital Systems Division

Recording Equipment, Magnetic Tape

Ampex Corporation
Bell and Howell, Electronics and Instruments Group
Cook Electric Company
Fairchild Industrial Products
General Instrument Corporation, Electronic Systems Division
General Radio Company
Hamilton Standard Division, United Aircraft
Hewlett-Packard
Honeywell, Inc., Aerospace and Defense Group
Lockheed Aircraft Corporation
Mincom Division, 3M Company
RCA
Scientific-Atlanta
Texas Instruments, Inc.

ADDENDUM F

REPRESENTATIVE STRUCTURE BORNE ACOUSTICS HARDWARE
SAMPLE — SPECIFICATIONS

The following data are included to provide a small sampling of the SBA hardware available off-the-shelf. Inclusion should not be construed as an endorsement of these products nor are the data necessarily current. Hardware in the following categories are included:

Accelerometer

Amplifier, Accelerometer

Analyzer, Averaging

Analyzer, Correlation and Probability

Analyzer, Real-Time

Analyzer, Spectrum

Correlator, Real-Time

Filter, Variable

Recorder, Tape, Magnetic

Recorder, X-Y

Scanner, Input

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MECHANICAL AND ELECTRONIC DEVELOPMENT ● INSTRUMENTS AND SPECIAL DEVICES

MINIATURE PIEZOELECTRIC ACCELEROMETERS
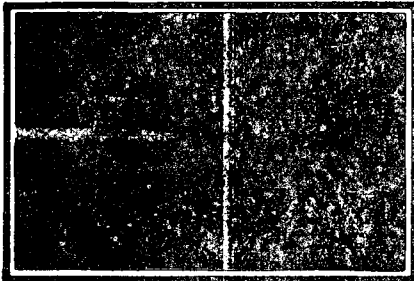
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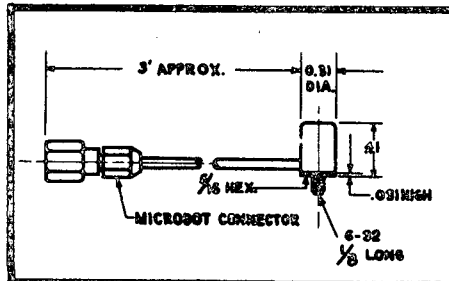
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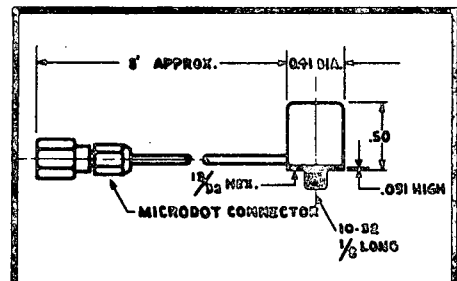
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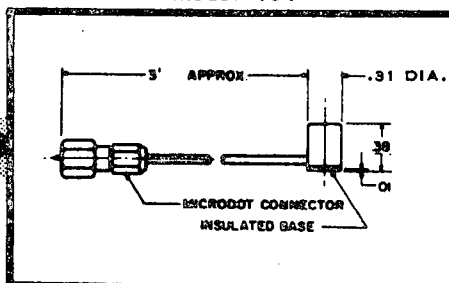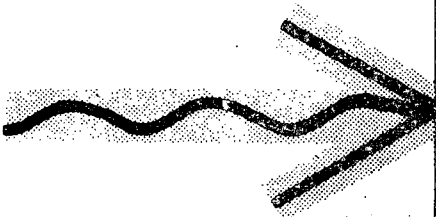
Model 111
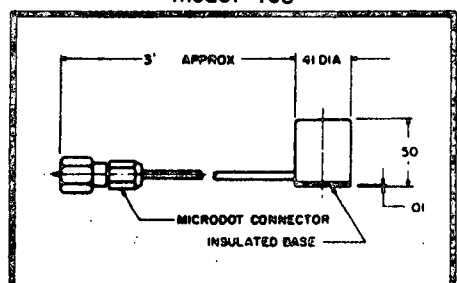
Model 113

● MODEL 111 ●	● MODEL 113 ●
1 gram	4 gram
6 mV/g	24 mV/g
1.2 pC/g	5 pC/g
$75.00	$75.00

The Model 111 and 113 accelerometers are recommended for reliable measurements on light structures since their low weight does not appreciably affect the motion of the structure. (See WR Bulletin No. 1 and No. 10).

Model 111 and 113 are cement-on types, Model 104 and 106 are supplied with threaded studs; and Model 112 and 114 are triaxials.

To reduce weight no connectors are used at the accelerometer. The cable connection at the accelerometer is extremely rugged. It will not break during normal usage and therefore no detachable cables are necessary.

SPECIFICATIONS	Models 104, 111	Models 106, 113
Charge Sensitivity, pC/g, nominal	1.2	5
minimum	1.0	4.0
Voltage Sensitivity, mV/g, nominal [1]	6	24
Frequency Response, Hz, ±½ db [2]	2 – 11,000	3 – 8,000
±1 db [2]	1 – 18,000	1.5 – 12,000
Capacitance, pF, nominal	200	200
Resonant Frequency, kHz, nominal [2]	55	36
Transverse Sensitivity, % of axial, nominal	5	3
maximum	10	5
Acoustic Sensitivity, equivalent g at 155 db re 0.0002 microbar, nominal [3]	2×10^{-1}	10^{-1}
Magnetic Sensitivity, equiv. g/gauss, nominal	10^{-4}	5×10^{-5}
Acceleration Range, g [5]	$10^{-2} – 10^{3}$	$3 \times 10^{-3} – 10^{3}$
Temperature Range, °F, ±10% sensitivity change	–60 to +250	–60 to +250
Humidity Range, percent	0 – 100	0 – 100
Nonlinearity, percent	1.5	1.5
Resistance, Megohm, minimum at 70° F	10^{3}	10^{3}
Weight, gram	1.2	4
Dimensions	See Drawing	See Drawing
Material of Base	S.S. 104 Alum. 111	S.S. 106 Alum. 113
Output Connector	Microdot at end of 3 Ft. cable	Microdot at end of 3 Ft. cable
Electrical Isolation of signal and case ground from test structure	Except 104	Except 106

	Mod. 104	Mod. 111	Mod. 106	Mod. 113
Price: 1 – 5 units	$95.00	$75.00	$95.00	$75.00
6 – 10 units	$85.50	$67.50	$85.50	$67.50
11 – 25 units	$81.00	$63.75	$81.00	$63.75

Options: A Triaxial Models 112, 114
Price $195.00 each

Calibration — Each unit is calibrated for sensitivity, transverse sensitivity, frequency response to one half of the resonant frequency, capacitance, This information is supplied with each transducer.

(1) With 100 pf external capacitance.
(2) Mounted on tungsten calibration table with 1,000 megohm electrical load.
(3) Tested in accordance with method described in Wilcoxon Research Bulletin No. 7.
(4) Tested in accordance with method described in Wilcoxon Research Bulletin No. 3.
(5) Minimum acceleration measured using Wilcoxon Research Preamplifiers without filtering with a signal to noise ratio of 10:1.

As a result of continuing research and development specifications and prices are subject to change without notice.

WILCOXON RESEARCH

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Phone (301) 365-4412

MECHANICAL AND ELECTRONIC DEVELOPMENT ○ INSTRUMENTS AND SPECIAL DEVICES

MINIATURE PIEZOELECTRIC ACCELEROMETERS
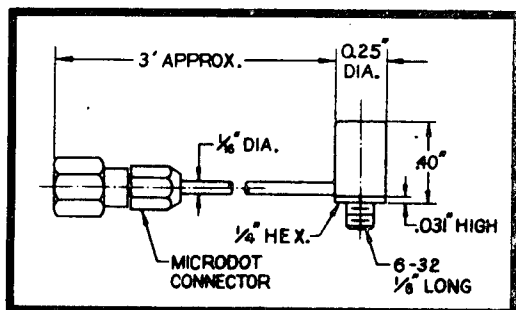
MODEL 96
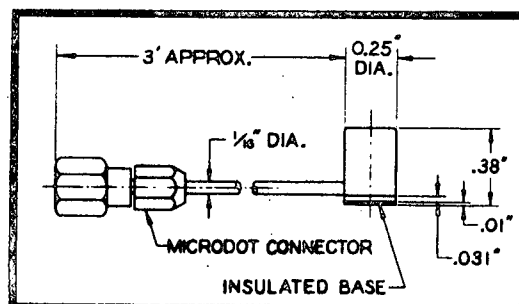
MODEL 95

MODEL 95

0.5 gram
1.5 mV/g
0.4 pC/g
1.5 - 23,000 Hz, ± 1 db

The Model 95 and 96 shear-type accelerometers are recommended for reliable measurements on light structures since their low weight does not appreciably affect the motion of the structure. (See WR Bulletins No. 1 and No. 10.)

Model 95 is a cement-on type, Model 96 is supplied with a threaded stud; and Model 97 is a triaxial accelerometer.

To reduce weight, no connectors are used at the accelerometer. The cable connection at the accelerometer is extremely rugged. It will not break during normal usage and, therefore, no detachable cables are necessary.

SPECIFICATIONS

Model	95	96
Charge Sensitivity, pC/g	0.4	0.4
Voltage Sensitivity, mV/g	1.5	1.5
Frequency Response, Hz, $\pm$ 1 db[1]	1.5-23,000	1.5-23,000
$\pm$ 3 db[1]	0.8-40,000	0.8-40,000
Capacitance, pF, nominal	250	250
Resonant Frequency, kHz, nominal	75	75
Transverse Sensitivity, % of axial, nominal	5	5
maximum	10	10
Acoustic Sensitivity, equivalent g at 155 db re 0.0002 microbar, nominal[2]	2×10^{-1}	2×10^{-1}
Strain Sensitivity, equivalent g at strain of 10^{-6} in plane of base, nominal[3]	2×10^{-3}	2×10^{-3}
Magnetic Sensitivity, equiv. g/gauss, nominal	10^{-4}	10^{-4}
Acceleration Range, g[4]	$0.01-10^{4}$	$0.01-10^{4}$
Temperature Range, ^{0}F, $\pm$ 10% sensitivity change	-60 to +250	-60 to +250
Humidity Range, percent	0-100	0-100
Nonlinearity, percent	1.5	1.5
Resistance, megohm, minimum at 70^{0}F	10^{3}	10^{3}
Weight, gram	0.5	0.8
Dimensions, inches, excluding connector	See Drawing	See Drawing
Material of Base	Aluminum	Titanium
Output Connector	Microdot at end of 3' cable	Microdot at end of 3' cable
Electrical isolation of signal and case ground from test structure	Yes	No
Price: 1 - 5 units	$ 95.00	$ 110.00
6 - 10 units	$ 85.50	$ 99.00
11 - 25 units	$ 81.00	$ 93.50
Options:	Triaxial Model 97, consisting of three Model 95 mounted on a 1/4" X 1/4" X 1/4" aluminum block. $285.00 each.	
Calibration:	Each unit is calibrated for sensitivity, transverse sensitivity, frequency response to one half of the resonant frequency, capacitance. This information is supplied with each transducer.	

(1) Mounted on tungsten calibration table with 1,000 megohm electrical load
(2) Tested in accordance with method described in Wilcoxon Research Bulletin No. 7
(3) Tested in accordance with method described in Wilcoxon Research Bulletin No. 3
(4) Minimum acceleration measured using Wilcoxon Research Preamplifiers without filtering with a
    signal to noise ratio of 10:1. Maximum acceleration for Model 95 depends on cementing technique.

As a result of continuing research and development specifications and prices are subject to change without notice.

WILCOXON MODEL AM-1
ACCELEROMETER AMPLIFIER
SPECIFICATIONS

VOLTAGE GAIN	Selectable steps:-10, 0, 10, 20, 30, 40 db ±0.2 db.Continuously variable attenuator 0 to -10 db
Gain Stability	±0.1 db
Bandwidth	3 to 100,000 cps ±3 db, optional at no additional cost 1 to 100,000 cps
Input Impedance	1,000 megohm shunted by 30 picofarad
Output Impedance	50 ohm maximum
Output Current	3 ma RMS short circuit
Input Voltage	5 volt RMS divided by gain for all gain settings
Power Requirements	-28 ±3 volt, 10 ma
Power Supply Noise Attenuation	40 db minimum at 60 cps referred to output
Temperature Range	0° to 50° C, operating
Terminals	Input BNC; Cal Input BNC; Output BNC

Broadband Noise referred to input, 5-100,000 cps, gain 40,30 or 20 db

Maximum
5 μvolt RMS with 1000 pf source
9 μvolt RMS with 200 pf source

Phase Shift
100 cps to 1 KC   1 degree absolute
20 cps to 10 KC   1 degree relative between any two AM-1 preamplifiers

As a result of continuing research and development specifications are subject to change without notice.
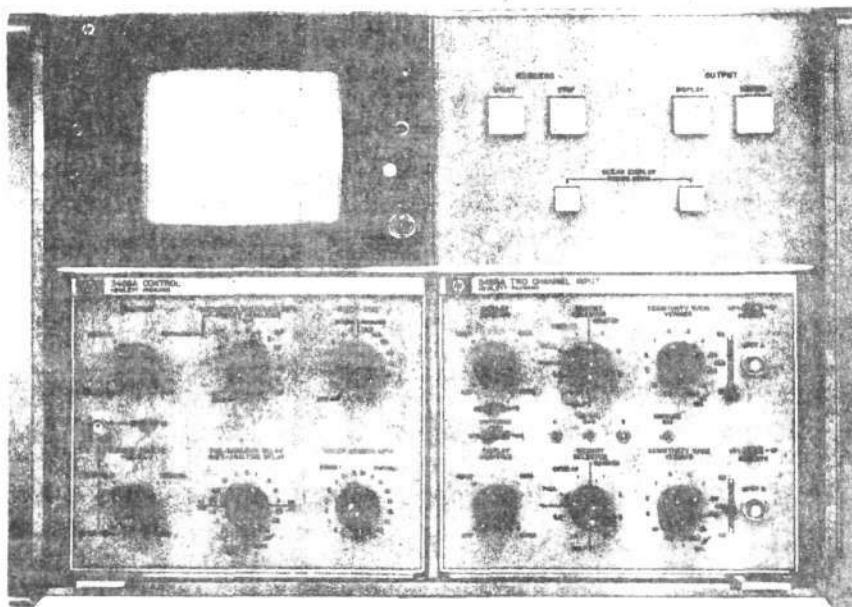
5480A Signal Averager

The Model 5480A Signal Analyzer applies statistical principles for real time analysis of data and signal-to-noise improvement. Accurate, detailed information is made available through signal averaging; an example of the results of this technique applied to nerve response is shown in Figure 1. Figure 2 shows the output of the HP 8553/8552 Spectrum Analyzer; the same spectrum enhanced by signal averaging is shown in Figure 3. Many other applications exist for the 5480A in the fields of medicine, bio-medicine, chemistry, physics, electronics, astronomy**, vibration, turbulence, and others.

The plug-in design of the 5480A provides a more versatile instrument and guards against obsolescence. The 5480A Mainframe contains a 1024 word, 24-bit magnetic core memory with related circuits and a CRT display while the two plug-ins chosen (5486A, and either the 5485A, 5487A or 5488A) depend upon the specific application.

Averaging

There are three methods of averaging that provide from 0 to 57 dB signal-to-noise ratio improvement.

Stable averaging: continuous calibrated on-line display. Signal amplitude remains constant as noise is attenuated.

Weighted averaging: permits signal enhancement of slowly varying waveforms by exponential weighting of previous information with respect to new information. SWEEP NUMBER setting determines speed at which the average signal follows input.

Summation averaging: algebraic summation process. Signal will grow from stable base line. If placed in AUTO mode, display will be automatically calibrated at the end of the preset number of sweeps.

*HP Journal, April '68   **HP Journal, June '69

Variance (Option 001): the variance of channel A is displayed by averaging the square of the noise in channel B.

Multichannel Scaling (MCS)

The analyzer sweeps through memory remaining at each channel for a preset time. A plot of the number of input pulses versus time is displayed.

Correlation

The frequency of a noisy signal can be obtained by auto-correlation, while the common frequency and relative phase difference of two noisy signals can be obtained by cross-correlation. The 5488A Plug-in is required for correlation.

Histograms

Probability density generation with respect to time interval and frequency.

Time interval: time between synchronization pulses. Horizontal calibration by time base.

Frequency: Start and stop determined by time base. Horizontal calibration by time base.
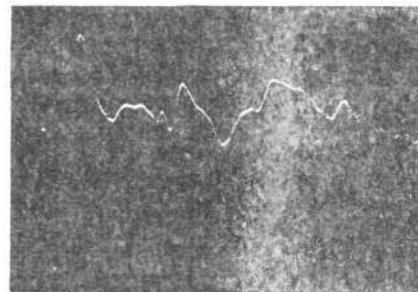
Figure 1. Evoked response, vestibular cortex of rhesus monkey.

General

Standard System Components

5460A	Display Plug-in
5465A	Analog-to-Digital Converter
5475A	Control Unit (keyboard console)
H51-180AR	Oscilloscope Mainframe
2115A	Digital Processor with 8192 word memory and Extended Arithmetic Unit
12566A	16-Bit Microcircuit Interface (two provided)
2752A	Teleprinter and Interface Card
2737A	Paper Tape Reader and Interface Card
2940A	Cabinet

Optional Components

2753A	High Speed Paper Tape Punch and Interface
7591A	Point Plotting System (requires option 005 and two each 17178A DC Attenuators)
2116B	Digital Processor with 8192 or 16,384 word memory (replaces 2115A Digital Processor in standard system)
12554A	Interface for binary data channel. One or two as required. (12556A may also be used)
Time Interval	Option (includes a 5235A Electronic Counter and necessary interfacing to the 5450A

Analog input

The 5465A Analog-to-Digital Converter accepts one or two inputs. In two channel operation both inputs are sampled simultaneously. Resolution of the ADC is 10 bits.

Amplitude range: 0.1 V to 10 V maximum in steps of 1,2,4,10.

Input impedance: 1 MΩ ±1% shunted by 45 pF max.

Sensitivity: 30 μV rms (sine wave).

Conversion gain (Channel A):

Accuracy (as function of frequency): ±0.1% ±3 x 10^{-3}%/Hz.

Temperature stability: 0.005%/°C.

Linearity: integral, ±0.05%; differential, ±3%.

Gain and phase Channel A to B:

Conversion gain A/B: ±0.2% ±2 x 10^{-4}%/Hz.

Temperature stability: 0.01%/°C.

Phase and delay A to B: ±0.2° ±0.5 μs.

Trigger modes: slope and level controls are provided. The trigger input can be ac or dc coupled.

Internal: ADC triggers on signal to Channel A.

External: ADC triggers on signal applied to external input.

Line: ADC triggers on power line frequency.

Free run: ADC triggers on data request from processor.

Digital accuracy and resolution

All calculations use floating point arithmetic on a block basis. Data overflow does not occur. Amplitude resolution is 1 part in 16,000 worst case.

Data memory size: 3072 words (8192 for a 16,384 word memory).

Data block size: any power of 2 from 64 to 1024 (to 4096 with a 16,384 word memory).

Data word size: 16 bit real and 16 bit imaginary or 16 bit magnitude and 16 bit phase.

Computational range: ±150 decades.

Transform accuracy: 0.1% worst case error during the forward or inverse calculation.

Computational speed

The following are typical operations and their analysis times. These times are reduced by 20% if the 2116B Digital Processor is used.

Fourier transform:

Block size 1024: 3.4 s for one data block or two independent data blocks simultaneously.

Block size 64: 130 ms for one data block or two independent data blocks simultaneously.

Power spectrum ensemble average:

Block size 1024: 2.4 s per spectral estimate (2 degrees of freedom).

Block size 64: 120 ms per spectral estimate (2 degrees of freedom).

Cross power spectrum ensemble average:

Block size 1024: 4.2 s per spectral estimate.

Block size 64: 220 ms per spectral estimate.

Spectral resolution

The element of spectral resolution is the frequency channel width, the maximum frequency divided by ½ the data block size.

Maximum frequency: 25 kHz single channel; 10 kHz dual channel. Adjustable in steps of 1,2,5 down to 0.2 Hz.

Frequency channel width: <3.2% down to <0.2% of the maximum frequency in steps of 2 (down to <0.05% for 16,384 word processor).

Spectral resolution of two equal amplitude sine waves: if separated by 3 frequency channel widths, there will be a null of at least 3 dB between them; if separated by 7 frequency channel widths the relative magnitudes will be correct to within 0.1%. The power spectrum for two equal amplitude sine waves separated by 5 frequency channels will have the correct relative magnitude to within 0.1%.

Dynamic range: 4 decades over ±150 decades.

Frequency accuracy: ±0.01%.

Time domain resolution

The element of time resolution is the time channel width, the time sample record length divided by the block size.

Maximum sample record length: product of data block size and time channel width. (In ensemble averaging up to 32,767 sample record lengths may be used for a statistical estimate.)

Time channel width: 20 μs, single channel; 50 μs, dual channel, up to 5 s in steps of 1,2,5. Accuracy 0.01%.

Display unit

Data may be displayed on the 8 x 10 cm oscilloscope or output to a plotter or remote oscilloscope in the following forms.

Y AXIS	X AXIS
Real Part Amplitude	Time
Real Part Amplitude	Frequency (Linear or Log)
Imaginary Part Amplitude	" " " "
Magnitude (Linear or Log)	" " " "
Phase	" " " "
Imaginary Part Amplitude (Nyquist Plot)	Real Part Amplitude

Analog display accuracy: ±1%.

Amplitude scale: data in memory is automatically scaled to give a maximum on-screen calibrated display. A scale factor is given in volts/division or volts²/division.

Linear display range: ±4 divisions with scale factor ranging from 1 x 10^{-150} to 5 x 10^{+150} in steps of 1,2,5.

Log display range: 4 decades with a scale factor ranging from 0 to —99.9 decades.

Time and frequency scale:

Linear sweep length: 10, 10.24, or 12.8 division.

Log horizontal: 0.5 decade/division.

Markers: intensity markers every 8th or every 32nd point.

Analog plotter output:

Amplitude: 0.5 V per oscilloscope display division.

Output range: 1-20 pts/s (500 pts/s external timing).

Linearity: 0.1% of full scale.

Power source: 115/230 V ±10%, 50/60 Hz.

Environmental conditions: +10°C to +40°C (0°C to 55°C using the 2116B Processor).

Price for the above referenced configuration using the 2115A Digital Processor is approximately $49,000.

Figure 2. Spectrum analysis using HP 8553/8552.

Figure 3. Enhanced spectrum analysis with the HP 5480A°.
°See Microwave Journal, October 1969.

Specifications

5486A Control Unit

S/N ratio improvement: up to 60 dB can be achieved.

Sweep number: manually selected. Dial is arranged in binary sequence (2^N) from single sweep (0 dial position) to 2^{19} (524,288) sweeps.

Sweep time (horizontal sweep): internally generated sweep time is calibrated in s/cm. Adjustable in 15 steps, in a 1, 2, 5 sequence, from 1 ms/cm to 50 s/cm. External sweep capability is provided.

Triggering and synchronization

Internal: sweep is triggered by internally generated pulse occuring at end of each sweep. Pulse available at back panel to control experiment; can be delayed by Post-Analysis Delay.

External: requires 100 mV rms signal ($+$ or $-$ slope) with rise time less than 10 μs.

Line: synchronized to power line frequency.

Pre-analysis delay: variable in 15 steps (1,2,5) from 20 μs to 0.5 s.

Post-analysis delay: continuously variable from 0.01 to 10 s.

Sensitivity multiplier: expands vertical to 64 counts/cm in power of two increments.

Input characteristics: (Histogram Mode).

Bandwidth: dc to 1 MHz.

Sensitivity: 100 mV.

Input impedance: 1 MΩ shunted by 30 pF.

5480A Outputs

Digital: two 50-pin connectors with binary data output. Direct interface with Hewlett-Packard computers is available with the 10625A Interface (5481A System).

Sweep voltage: 0 to $+1$ V sweep ramp; conveniently adjusted by changing resistors to give output ramp going from 0 V to any value between 0 to $+10$ V.

Sync: "Pos" provides $+12$ V, >0.5 μs pulse at start of each sweep (before pre-analysis delay); "Neg" provides same except -12 V.

Sampling pulses: pulses (100 ns pulse width) go from $+5$ V to ground and return to $+5$ V once each time the input is sampled.

Analog: X and Y outputs for Recorder, Point Plotter, Scopes, NMR Systems.

General

Power: 115 or 230 V $\pm 10\%$, 50-400 Hz, 175 watts.

Dimensions: 16¾" wide, 12½" high, 24⅜" deep over-all (425 x 311 x 593 mm).

Weight: 76 lb (34,5 kg) net with plug-ins.

5485A Two Channel Input

Input characteristics: two channels with polarity switch for each channel. Channels can be used individually or their inputs can be summed.

Coupling: ac or dc.

Input impedance: exceeds 1 MΩ shunted by 25 pF.

Bandwidth: from dc (2 Hz ac coupled) to 50 kHz.

Sampling rate: 2 Hz to 100 kHz, in 1,2,5 steps.

Input sensitivity: adjustable from 5 mV/cm to 20 V/cm in 12 steps (1,2,5 sequence) with $\pm 3\%$ accuracy. HP amplifiers, Models 2470A or 8875A, may be used to increase sensitivity.

Analog-to-digital converter: ramp type with variable resolution 1 ms/cm sweep time has 5 bit resolution. 2 ms/cm sweep time has 7 bit resolution. 5 ms/cm or slower sweep time has 9 bit resolution. ADC clock rate 10 MHz.

Pulse requirements: (Multichannel Scaling Mode)

Amplitude: >2 V (20 V max).

Maximum repetition rate: 1 MHz.

Minimum pulse width: 500 ns.

Pulse pair resolution: 500 ns.

Input impedance: 3 kΩ minimum.

Dwell time per channel: 10 μs through 0.5 s in 1,2,5 steps (external time base: 50 μs to ∞).

Sweep modes: sawtooth. External time base input allows any desired sweep shape.

Triggering: external or internal.

5487A Four Channel Input

Same as 5485A except four inputs, deletes summing of inputs and polarity inversion.

Bandwidth: dc (2 Hz dc coupled) to 25 kHz.

Sensitivity: 50 mV/cm to 20 V/cm.

5488A Correlator Input

Same as 5485A except adds correlation, deletes summing of two inputs, and polarity inversion.

Bandwidth: dc (2 Hz ac coupled) to 25 kHz.

Sensitivity: 50 mV/cm to 20 V/cm.

Price:

5480A Mainframe, $6950.

5485A Two-Channel Input, $1500.

5486A Control Unit, $1500.

5487A Four-Channel Input, $1800.

5488A Correlator Input, $2500.

Option 001 Variance, add $300.

SAICOR

NCW!
RESOLUTION TO .2usec
FASTER PROCESS...

NEW 400 Point
model sai-43

CORRELATION
& PROBABILITY
ANALYZER
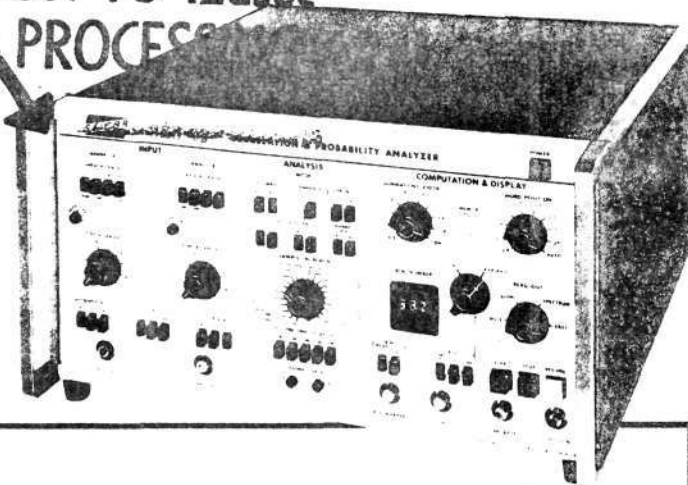
The SAI-43 Correlation and Probability Analyzer is an all-digital high speed processing instrument which provides an on-line, real time computation in three primary operating modes— Correlation (auto and cross), Enhancement (or signal recovery) and Probability (Density and Distribution). In all modes, 400 analysis points are computed.

CORRELATION: Correlation is a fundamental time domain processing tool in which waveform similarities are established thru time delay comparisons. In autocorrelation a signal is compared with a time shifted version of itself. In crosscorrelation the similiarity between two signals is determined as a function of the time shift between them.

The SAI-43 provides auto and crosscorrelation functions with incremental lag or time delay values ranging from 1 usec to 1 sec resulting in total time delays from 400 usec to 400 sec. Auto or crosscorrelation functions are determined simultaneously at 400 incremental lag points so that a complete correlation function is displayed at one time. Precomputation delay of 800 lag values selected in 200 lag increments allows the correlation function to be viewed symmetrically about zero or up to 800 lag values removed from zero (optionally to 8000 points). The clipped mode allows rapid determination of time dependencies for low level signals. The averaging is accomplished digitally with fixed linear summations ranging from 2^9 to 2^{17} in binary steps. Exponential averaging is a standard feature.

ENHANCEMENT: Some waveforms are periodic with a known period or are periodically stimulated as in a stimulus-and-response application. Often these waveforms are buried in random or non-coherent interference. The Enhance mode of the SAI-43 allows for the detection of the actual waveshape of this repetitive waveform through a signal averaging or so-called enhancement procedure.

The waveform is divided into 400 points with resolutions (or spacing between points) ranging from 1 usec to 1 sec. From 2^9 to 2^{17} (in binary steps) successive pulses can be linearly averaged in addition to the continuous operation mode. Exponential averaging of the pulses is also available. This mode is operable with either an externally applied synchronization pulse or an internal pulse provided at the rear panel.

PROBABILITY: Probability analysis provides a description of the instantaneous amplitude characteristics of a waveform. The probability density function (DENS) provides information concerning the likelihood that a function lies within prescribed (amplitude) bounds. The probability that the signal amplitude will not exceed a particular value is provided by the probability distribution function (DIST).

In the probability mode the functions are determined at 400 points. The horizontal axis of the display represents voltage and the range and sensitivity are determined by the setting of the input attenuators. Here again the averaging process is linear and is also available exponentially.

new 400 point
model sai-43

CORRELATION
& PROBABILITY
ANALYZER

OPERATING MODES:

Correlation — Probability — Signal Enhancement

INPUT (each channel)
Two identical, independent channels (A and B)
Full scale input: 100 MV RMS (sine wave)
Impedance: 50KΩ NOM shunted by <30 pf
Attenuator: 39 dB total in 1 dB steps
Full scale: Peak full scale indicator
Coupling: DC and AC (3 dB corner @ 1Hz)
Maximum input: 200 V peak
Dynamic Range: 48dB
Maximum Freq.: Input Amplifiers down 3db @ 250 KHz

CORRELATION MODE:

Auto and cross correlation: 400 lag values; simultaneous computation and display
Time Scale: 1 μsec to 1 sec (total delay span from 400 μsec to 400 sec) in 1, 2, 5 sequence with internal clock. Other delay increments with external clock 1 μsec, min., no upper limit.
Standard precomputation Delay: First point selectable from 0 to —800 Δt in multiples of 200 Δt.
Optional precomp delay to 4000 Δt in multiples of 200 Δt.
Optional precomp delay to 8000 Δt in multiples of 200 Δt.
Quantization Full: Effective 8 bits each channel
        Clipped: One bit quantization each channel
Averaging: Linear — switch selectable from 512 to 128 x 1024 sums/Point in powers of two. Resume Integration permits retention of previous sums and accumulation of new additional average. Start, Stop and Resume commands manual and remote. A continuous average selection results in averaging until any word storage reaches saturation at which point averaging automatically stops. Overriding STOP control permits any predetermined number of sums/point.
    Automatic *Reset and Repeat* provides a pseudo-continuous averaging mode for continuous signals. This provides the continuous processing associated with exponential averaging with the accuracy and signal enhancement associated with linear averaging.
    Digital exponential (RC) averaging — same range selection as in linear.
Vertical Resolution: One part in 256 switch selectable over a 2⁹ range plus automatic mode. In automatic mode a full scale input signal results in full scale presentation of the correlation function regardless of integration switch position.

PROBABILITY MODE:

Probability density function (p.d.f.) and Probability distribution (integral of p.d.f.); 400 discrete levels (channel A or channel B)
Density Vertical Resolution: One part in 128 with highest level normalized to 100%
Distribution Vertical Resolution: One part in 128, switch selectable over a 2⁹ range plus automatic mode as in correlation. Manual override, as in correlation.
Measurements per Function: Linear — switch selectable from 512 to 128 x 1024 per point. See correlation mode discussion of averaging flexibility. Exponential averaging available.
Horizontal Resolution: 400 discrete voltage bins; full scale established by input attenuator settings
Sampling rate: 1 Hz to 10 KHz in 1, 2, 5, sequence. Other sampling rates with external clock; max rate 10 KHz, no lower frequency limit

SIGNAL ENHANCEMENT MODES:

Detects coherence in repeated events. After internal or external synch pulse, a series of 400 samples is taken and corresponding samples from each series are averaged. The 400 averaged samples are simultaneously collected and displayed.
Vertical resolution: one part in 256, switch selectable over a range of 2⁹ plus automatic mode as for correlator.
Synchronization: Either internally or externally triggered. In internal trigger, the start or sync point is marked by an output pulse (stimulus) used to sync some external event.
External trigger: Positive, peak amplitude from 2.4V to 5V (see time scale) width 1μs min.
Internal trigger: Stimulus output positive pulse 2.4 to 5V., Width 1 sample period.
Time Scale: (interval between samples) 1 μsec to 1 sec, 1, 2, 5 sequence. Other intervals available with external sample, min interval 1 μsec, no upper limit.
Number of sums per point: Linear — from 512 to 128 x 1024 in powers of 2. Exponential averaging available.
Improvement: Improvement in S/N equals square root of number of sums.

OUTPUT MODES:

Oscilloscope: Trigger pulse provided for external synchronization of oscilloscope. All functions displayed continuously during and after processing on a 40 Msec time base (flicker free).

Spectrum: Correlation functions presented continuously after processing (compatible with Saicor SAI-51 Spectrum Analyzer) for providing spectrum analysis of correlation functions.

Record: Functions presented continuously after processing with a 16 second time base for use with chart recorders.

Plot: Function presented during one 64-second sweep (for use with X-Y plotters) when "Plot" button is depressed. Calibration signals: Zero CAL depressed X = 0, Y = 0; FULL CAL depressed X = full scale, Y = full scale.

Bin Marker: Positive, 15V pulse, position located by BIN number thumbwheel. Depression of "BIN Readout" button causes value of function at selected location to appear as a DC voltage at function jack.

Digital Outputs (optional):
Binary:
    Correlation Functions — 2's complement 8 bits for amplitude
    Probability Functions — 7 bits for amplitude
    Enhanced Function — 2's complement 8 bits for amplitude
    Bin Number (all modes) — 7 bits

BCD:

Correlation function	3 Decimal digits + sign
Probability function	2 Decimal digits (always +)
Enhance	3 Decimal digits + sign
Bin number	3 Decimal digits

    Format: "1" equals 2.4 V min, 5 V max.
            "0" equals 0 V min, 0.4 max.

Programming Capabilities: Remote start, stop, resume (with override capability)
    External sample and sync inputs
    All front panel connections appear in parallel on the rear panel
    Remote selection of optional precomputation delay

MECHANICAL AND GENERAL

Ambient Temperature Range: 0°C to 45°C
  Power: 115/220V AC, 50-60 Hz
Dimensions: 8¾" H x 17½" W x 23" D
  Weight: 44 lbs.
  Optional Rack Mounting Available

SAICOR

Specifications subject to change.

SIGNAL ANALYSIS INDUSTRIES CORPORATION
595 OLD WILLETS PATH, HAUPPAUGE, NEW YORK 11787 / 516-234-5700

real-time
1/3 octave analyzer

Features:
- Full-time detection gives repeatable accuracy for single impulsive signals
- All 38 detector time constants individually adjustable from 20 msec to 60 sec to meet varying requirements
- Digital readout possibility for complete spectrum every 2 msec, independent of time constant
- Easy to read 12″ bargraph display with electronically generated grid lines giving 0.2 dB resolution
- RMS detection range of 64 dB, display range 50 dB giving full-scale crest factor of 5 (14 dB)
- Internal reference and transducer normalising systems produce direct reading in dB on scope, digital, and meter display

Uses:
- Analysis of non-stationary pass-by or impulsive type signals
- Continuous high-speed analysis. Max. readout rate 2 msec per spectrum for handling large amounts of data or multiple test stations in quality control (during time sharing)
- Analysis and Analog/Digital conversion for computer processing to obtain complex relationships or statistical comparisons
- Visual demonstration of data significance as needed for signature analysis, pattern recognition, data editing, and monitoring
- Fast frequency response plots from pink noise excitation
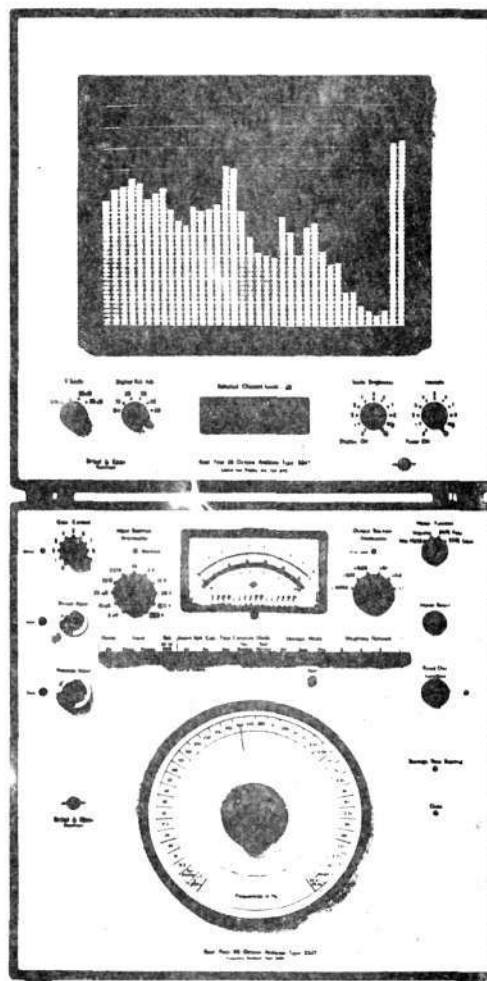
B&K INSTRUMENTS, INC.
Bruel & Kjaer Precision Instruments

Frequency Analyzer Type 2130

Output Amplifier — Detector — Meter

To Level Recorder "Selected Filter Output"

To Level Recorder "Multiplexer Output"

Direct Input

Preampl. Input

First Amplifier

Filter — Detector — Integrator — Store — FET Gate — Buffer

Analog Signal to 4710

Attenuator Pos.

Channel Advance

To logic control in 4710

Time Constant Mode
Sine
Fast Random
Slow Random

Storage Mode
Off
Store
Max.

50 pos. Switch

Logic Control

Attenuator Information

Sync. Signals from Level Recorder

Control and Display Unit Type 4710

Exponential Slopes

Manual or Automatic Selection

50 dB
25 dB
10 dB
(Lin)

Comparator

Video Mixer

Display Scope

Analog Signal from 2130

Video

y-Deflex

Logic Control

x-Deflex

Control Signals to and from 2130

5 dB, 1 dB, & 0.2 dB
Indication Pulses

7.5 MHz Master Osc.

Frequency Dividers

A/D Converter

Adder

Attenuator Info. from 2130

Data Control Lines

Data BCD Output Lines

BCD-Decimal Converter

Nixie Tube Display

Fig. 1. Block diagram of the Real-Time 1/3 Octave Analyzer Type 3347.

Df-13

Frequency Analyzer
Type 2130

Amplifiers:

Input:
Either "Direct Input" or standard B & K 7 pin "Preamplifier Input".

Input Impedance:
Direct: 1 MΩ//50 pF.
Preamp.: 900 kΩ//50 pF.

Input Voltage:
10 μV to 300 V for full meter scale deflection.

Input Section Attenuator:
3 mV – 300 V in 10 dB steps.
Accurate to within ± 0.1 dB at 1 kHz relative to "100 mV" position.

Output Section Attenuator:
x 0.003, x 0.01, x 0.03, x 0.1, x 0.3 and x 1.
Accurate to within ± 0.1 dB at 1000 Hz relative to "x 1" position.

Gain Control:
0 to – 10 dB.

Sensitivity Adjustment (DIRECT):
+ 4 dB to – 10 dB.

Sensitivity Adjustment (PREAMP.):
+ 4 dB to – 10 dB.

Overload Indicators:

Input Amplifier: Indicator lights for overload pulse > 5.6 V peak, 1 msec and remains lit for 0.5 sec minimum.

Output Amplifier: Indicator lights for overload pulse > 56 V peak, 1 msec and remains lit for 0.5 sec minimum.

Frequency Range:
10 Hz to 50 kHz, ± 0.2 dB.
2 Hz to 200 kHz, ± 0.5 dB.

Analogue Read out:
From Meter or via "Selected Filter Output" socket.

Channel Selector:

50 position switch for manual selection of filters, weighting, and linear networks for analogue and Nixie tube read out.

Filters:

1/3 Octave Filters:
30 filters with centre frequencies from 25 Hz to 20 kHz to IEC 225-1966 and DIN 45 652. Fulfils ANSI S1.11-1966 Class III for passband and Class II for rejection. With 6 optional filters the range can be extended to 12.5 Hz to 40 kHz.

Weighting Networks:
Curve A, B and C to IEC 179-1965. Curve D to IEC proposal for measurement of jet engine noise.
Filter selection via front panel push buttons.

Linear Filter:
Linear band pass filter with cut off frequencies 22.4 Hz and 22.4 kHz (attenuation approx. 24 dB/Octave from band limits).

Linear Range:
Lin 2 Hz – 200 kHz (analogue read out only).

Meter:

Indicates the signal level in the channel selected by the 50-position dial.

Meter Functions:
RMS "Fast" and "Slow" to IEC 179-1965.
"Impulse" to DIN 45 633 pt. 2 and to proposed IEC 179 extension.
"Impulse Hold" indicates maximum RMS level of input signal. Decay rate less than 0.5 dB/sec at 25°C.

Crest Factor Capability:
10 at F.S.D. increasing to 40 at 12 dB below F.S.D.

Accuracy of Meter Circuits:
For Signal Crest Factor < 10: ± 0.5 dB from 0–12 dB below F.S.D.
± 1 dB from 12–20 dB below F.S.D.
For Signal Crest Factor between 10 and 20: Add 0.5 dB to above values.
For Signal Crest Factor between 20 and 40: Add 1 dB above values.

Selected Filter Output Socket:

AC:
Output Impedance: < 50 Ω.
Minimum Load Impedance: 5 kΩ.
Output for Full Scale Meter Deflection: 5 V RMS.
Maximum Output: 56 V peak.

DC:
Output Impedance: 25 kΩ.
Minimum Load Impedance: 5 kΩ.
Output for Full Scale Meter Deflection: – 0.9 V.
Maximum Output: – 2.2 V.

RMS Detectors:

Accuracy:
True RMS detection of the output from filters, weighting, and linear networks. 50 dB dynamic range for digital read out with the following tolerance levels at room temperatures (25°C).

Steady Sine Wave at Filter Centre Frequency:
0–20 dB below F.S.D. ± 0.2 dB
20–30 dB below F.S.D. ± 0.5 dB
30–40 dB below F.S.D. ± 1 dB
40–50 dB below F.S.D. ± 1.5 dB

For Tone Bursts with Crest Factor 5:
0–20 dB below F.S.D. ± 0.5 dB
20–30 dB below F.S.D. ± 1 dB
30–40 dB below F.S.D. ± 1.5 dB
40–50 dB below F.S.D. ± 2 dB

In environments with large temperature variations over the range 5°C to 40°C, the figures for 40–50 dB below F.S.D. are increased to ± 3 dB and ± 3.5 dB respectively.

Time Constants:

1/3 Octave Filter Detectors:
"Sine": 0.2 sec above 200 Hz. Below 200 Hz the time constant rises with decreasing centre frequency to 3.15 sec at 12.5 Hz.
"Fast Random": 0.2 sec above 2 kHz. Below 2 kHz the time constant rises with decreasing centre frequency to 20 sec at 20 Hz and thereafter remains constant.
"Slow Random": 20 sec from 12.5 Hz to 40 kHz.

Weighting and Linear Filter detectors:
(Detector for lin. filter to be ordered separately).
"Sine": 70 msec (Rise curve 35 msec). To approximate IEC 179 proposal and DIN 45633 pt. 2 "Impulse" when used together with 'Store Max".
"Fast Random': 240 msec. To IEC 179 "RMS Fast".
"Slow Random: 1.5 sec. To IEC 179 "RMS Slow".
Other time constants in the 20 msec to 60 sec range can be supplied on special order or by internal modification.

Storage Modes:
"Off":For continuous read out of the RMS value of a signal.
"Store": For read out of the instantaneous value of a signal at any particular instant.
"Max": For read out of the maximum RMS signal value.
Maximum error in "Store" and "Max" modes with continuous scanning (CRT display) at room temperature (25°C).
Range 0–20 dB below F.S.D. + 0, – 0.3 dB/min.
Range 20–40 dB below F.S.D. +0.5, – 1 dB/min.
Range 40–50 dB below F.S.D. ± 1.5 dB/min.
Maximum error in "Store" and "Max" modes with single scan (Multiplexer Output):
Range 0–35 dB below F.S.D. +0, – 0.3 dB/min.
Range 35–50 dB below F.S.D. ± 1 dB/min.

Multiplexer Output:

Output Impedance:
< 1 Ω.

Minimum Load Impedance:
10 kΩ.

Output (FSD):
+ 7.0 V.

Max. Output:
± 15 V (unloaded).

Power Supply:
100, 115, 127, 150, 220, 240 Volts AC ± 10 %.
50–60 Hz. 110 Watts approx.

Environment:
Temperature Range:
(for operation within specifications) +5°C to + 40°C.
Storage Temperature:
– 25°C to + 60°C.
Heating resistors for environments with high humidity can be supplied on special order.

Cabinet:
Supplied as model A (light-weight metal cabinet), B (model A in mahogany cabinet) or C (as A but with flanges for standard 19" racks).

Dimensions and Weight:
(A-cabinet)
Height: 380 mm (15 in)
Width: 380 mm (15 in)
Depth: 350 mm (13.75 in)
Weight: 26 kg (55 lb)

Control and Display Unit Type 4710

Cathode Ray Tube Display:
Display Area:
17.5 cm × 23.5 cm (7 in × 9 in).
Scale Lines:
51 lines are produced electronically directly on the screen for parallax-free readings. Scales change automatically to fit the Y-range.
Representation of Channels:
In 38 columns, 36 for the 1/3 octave filters, 1 for the weighting networks, and 1 for the linear pass-band (optional version).
Each channel represented by a column consisting of 10 CRT lines one of which is darkened for column separation.
Plexiglass scale identifies 1/3 octave filter centre frequencies in Hz, weighting filter and Lin. filter.

Brightness Control:
Potentiometer regulation of scale lines and frequency spectrum. Scale brightness can also be varied independently, permitting fade-out so that only the frequency spectrum is seen.

Overload:
Storage Mode "Off" (2130): CRT display brightened when output of Input Section Amplifier (of 2130) exceeds 5.6 V peak.

Storage Mode "Store" (2130): CRT display is kept brightened if output of Input Section Amplifier (of 2130) exceeded 5.6 V peak when "Store" was selected.

Storage Mode "Max" (2130): CRT display will be brightened and kept brightened when output of Input Section Amplifier (of 2130) exceeds 5.6 V peak.

Master Oscillator:
7.5 MHz crystal controlled oscillator for logic circuitry as well as CRT line and frame frequencies.

Line Frequency:
18.75 kHz (53.33 μsec per line).

Frame Frequency:
46.875 Hz (400 lines per frame).

Digital Display:
Read Out:
4 digit Nixie tube display of selected channel level in range 50 dB, or CRT reference level in range 50, 25, or 10 dB.

Figure Height:
13 mm (0.51 in).

Max. Reading:
200.0 dB.

Resolution:
0.2 dB.

Digital Read-Out:
Read Out:
14 bit transfer of 4 digits in 8–4–2–1 BCD Code. Range 0 to 200 dB. (For 12 bit transfer the range is 0 to 199.8 dB).

Logic Levels:
"1": + 2.4 V to 5.0 V.
"0": 0 V to + 0.4 V.

Control Signals:
From 3347:
Data Ready.
End of Scan.
Manual Start.
Under-range.
Over-range.
Overload.
To 3347:
Data Request.

Data Received.
Auto Store.

Read Out Time:
(Minimum): Between 2.13 msec and 2.23 msec. (For "Y Scale" in pos. 50 dB and a 14 bits data acception time of min. 6.6 μsec). For Y scale in "Lin", "10 dB" and "25 dB" positions the read-out time is increased by approx. 1 msec.

(Maximum): With the STORAGE MODE in "Store" or "Max" read-out time is limited only by the leakage error of the store circuits. See 2130 specifications.

Dynamic Range:
50 dB irrespective of the Y SCALE control setting.

Resolution:
0.2 dB.

Power Supply:
100, 115, 127, 150, 220, 240 Volts AC ± 10 %.
50–60 Hz. 40 Watts approx.

Environment:
Temperature Range (for operation within specifications):
+ 5°C to + 40°C.

Storage Temperature:
– 25°C to + 60°C.

Cabinet:
Supplied as model A (light-weight metal cabinet), B (model A in mahogany cabinet) or C (as A but with flanges for standard 19″ racks).

Dimensions and Weight:
A-cabinet
Height: 380 mm (15 in)
Width: 380 mm (15 in)
Depth: 350 mm (13.75 in)
Weight: 15.5 kg (32.5 lb)

Accessories Included with Type 3347
Plugs and Cables:
2 × AN 0005 (or AN 0006): Mains cable European (or American).
2 × AO 0013: B & K coaxial cable.
1 × AO 0065: Control cable for connection between 2130 and 4710.
1 × AO 0075: Level Recorder control cable (2305).
1 × AQ 0025: Pen Lift control cable (2305).
1 × JP 2401: 24 pin plug for "Digital Output".

Meter Scales:
SA 0037: Voltage Scale (with dB). (Fitted on delivery).
SA 0038: Voltage Scale in dB re 1 μV.

SA 0039: Sound Level Scale (dB re 2×10^{-5} N/m²) for microphones of sensitivity 26–90 mV per N/m².

SA 0061: Sound Level Scale (dB re 2×10^{-5} N/m²) for microphones of sensitivity 0.8–2.6 mV per N/m².

SA 0071: Acceleration Scale (with dB) for accelerometers of sensitivity 6–17 mV/g.

SA 0086: Scale with 100 divisions.

SA 0091: Sound Level Scale (dB re 2×10^{-5} N/m²) for microphones of sensitivity 9–26 mV per N/m².

SA 0092: Sound Level Scale (dB re 2×10^{-5} N/m²) for microphones of sensitivity 2.6–9 mV per N/m².

Miscellaneous:
3 × DK 0168: Meter scale lock.
1 × SD 0008: Light shield for 4710 CRT display.
1 × QA 0001: Screwdriver.
Various lamps and fuses.

Accessories Available:
Filters and Detectors:
ZT 0997 12.5 Hz filter and detector
ZT 0998 16 Hz filter and detector
ZT 0999 20 Hz filter and detector
ZS 1010 25 kHz and 31.5 kHz filters and detectors

ZS 1011 40 kHz filter and detector
Together with one or more of the above mentioned filters one
ZH 0026 Scanner must be ordered
ZL 0010 Detector for Lin. filter

Meter Scales:
SA 0070: Acceleration Scale (with dB) for accelerometers of sensitivity 17–60 mV/g.

SA 0074: As above, but for accelerometers of sensitivity 1.7–6 mV/g.

SA 0075: As above, but for accelerometers of sensitivity 60–170 mV/g.

SA 0077: dBm scale.
dB above 1 volt and dB above 0.775 volts.

Other Options:
AR 0500: A set of extension boards and a print extractor (for service use).
GS 0247: Heavy μ-metal screen for 4710 CRT.
KQ 0092: Rack for mounting 2130, 4710 and 2305.
KS 0018: Rack mounting frame for 2130 and 4710 (conversion to "C" model, 2 required).
ZH 0045: X–Y Recorder Control.
RM 2002: Tropicalisation unit (set of heating resistors).
UA 0328: Blank plexiglass scale.

Specifications X-Y Recorder Control ZH 0045 (optional)

X Deflection:
Read Out Time:
20, 50 or 100 sec. A clock generator steps the Multiplexer in the 2130.

Reset Time:
1 sec delay from completion of X scan to when pen starts to move back to start position of recording chart.
8 sec delay for calibration of X deflection when CHANNEL SELECTOR set to "Ref. Display".

Ramp Voltage:
0 to 5 V (linearity better than ± 0.5 % of full scale deflection).

Output Impedance:
< 1 Ω. X output short circuit protected.

Minimum Load Impedance:
10 kΩ.

Y Deflection:
A log amplifier is incorporated in ZH 0045 to obtain a linear dB scale for X–Y recording.

Output Voltage:
For 50 dB: + 5 V (100 mV/dB).
For 0 dB: 0 V.
For < 0 dB: 0 V.

Minimum Load Impedance:
10 kΩ.

Output Voltage Accuracy:
± 0.4 dB (5°C – 40°C).
+ 0, – 0.3 dB (room temperature).

Output Impedance:
< 1 Ω. Y output short circuit protected.

Accessories Supplied:
AO 0076 Cable for connection of X deflection.
AO 0024 Cable for Pen Lift control.

- 3.15 Hz to 80 kHz
- 30 to 45 channels
  1/1, 1/3, 1/10 octave bands
- 70-dB dynamic range
- 60-dB display range
- calibrated attenuators
- true rms detection
- 9 integration periods
- corrected spectrum
  displayed directly
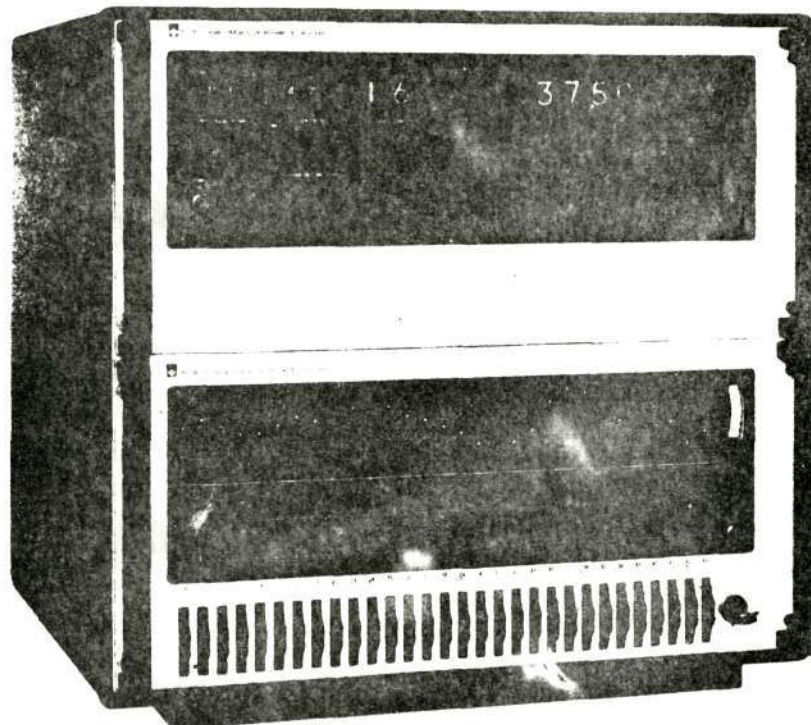
The Type 1921 Real-Time Analyzer is a new-generation analyzer. It performs real-time one-third-octave spectrum analysis in the frequency range from 3.15 Hz to 80 kHz employing a unique digital detection scheme to achieve performance unattainable with analog techniques. The major components of the analyzer are the Type 1925 Multifilter and the Type 1926 Multichannel RMS Detector.

Filters in the 1925 conform to American and International standards. The Multifilter includes a calibrated attenuator in each filter channel to permit pre-whitening or weighting. The attenuators can also be used to correct transducer or tape-recorder errors or to extend the dynamic range of the analyzer. The attenuation is controlled by individual thumbwheels and indicated on a panel display. The Multifilter also includes A-, B-, and C-weighting networks.

The Type 1926 Multichannel RMS Detector is unique in that it processes the signal from the Multifilter digitally. The outputs of the filters are sampled, the sample data converted to digital binary form, and the binary numbers fed to a digital processor which computes root-mean-square level. There are several advantages in this method of rms detection as compared with analog methods. A very wide dynamic range can be realized while maintaining an accurate rms characteristic.

The averaging method is true (linear) integration with a choice of nine integration periods from 1/8 second to 32 seconds. A true integration scheme not only gives answers faster than the running average circuits found in analog devices (they "waste" time and are not very useful for transient signals) but also makes it possible to determine exactly what events in time have affected the answer. The

computed band levels are stored in a digital memory to be retrieved at a rate limited only by the output recording or storage device. The analyzer simultaneously produces both digital (1-2-4-8 code) and analog outputs.

The 1921 is available in eight standard 30-channel versions including four versions with adjustable calibrated attenuators and four without. The four standard three-decade frequency ranges include bands extending down to 3.15 Hz and up to 80 kHz. A-, B-, and C-weighted sound level as well as a flat frequency-response channel are available for all versions. The analyzer's filter section

(Type 1925 Multifilter) can also function as a spectrum synthesizer, equalizer, or shaper.

The 1921 Real-Time Analyzer has also been designed to allow great flexibility in the number and bandwidths of filters and for input and output devices. Custom versions with up to 45 channels, octave bands, mixtures of octave, one-third-octave, and one-tenth-octave bands, and special bandwidths can be supplied. Complete custom systems from transducer to final data storage (or even including a computer for rapid data storage, determining ratings, making comparisons, etc) can also be supplied.

— See GR Experimenter for May-June 1969.

specifications

OPERATIONAL CHARACTERISTICS

Frequency Range: 30 1/3-octave filter channels from 3.15 Hz to 80 kHz in standard models (see table).
Dynamic Range: 70 dB; 60-dB range is displayed, thus allowing a crest-factor margin of 10 dB at full scale.
Sensitivity: 0.1 V rms nominal for full scale. Can be increased to 5 mV full scale with GR 1560-P40 Preamplifier (power supplied by 1921).

INPUT

Impedance: 100 kΩ.
Voltage: AC component, ± 17 V pk max referred to dc component of input. DC component, ± 35 V max.
Gain Adjustment: 18 dB continuous, common to all channels.
Peak Monitor: A peak detector senses levels at two circuit points and drives a panel meter calibrated in dB referred to overload level. A signal proportional to meter deviation is available at an output jack for driving a dc recorder; 1 mA corresponds to full-scale reading.

FILTERS

Characteristics: One-third-octave effective (noise) bandwidths. Filters are six-pole Butterworth designs and meet current American and International standards: 1/3-octave filters conform to ANSI S1.11-1966 Class III (high attenuation) and IEC Recommendation Publication 225-1966.
Accuracy of Center Frequency: ±2%.
Passband Ripple: 0.5 dB max pk-pk.
Uniformity of Levels (at center frequencies, attenuator at +25 dB): ±0.25 dB at 25°C; ±0.5 dB, 0 to 50°C.
Noise: <15 µV equivalent input noise.
Harmonic Distortion (at band centers): For bands centered at 25 Hz and above, <0.1% at 1-V output. For bands below 25 Hz, <0.25% at 1-V output.
Weighting: A, B, and C characteristics of weighted channels conform to current American and International standards including ANSI S1.4, IEC R123, and IEC R179.

ATTENUATORS

Range: Gain in each filter channel adjustable in 1-dB steps over a range of 50 dB by front-panel controls.
Accuracy: ±0.25 dB relative to indicated +25-dB setting.
Readout: Panel display indicates attenuation in each channel and represents the transmission between input and summed output of multifilter. Display has standard 50-dB-per-decade scale factor; 10 dB per inch vertical, 5 inches per decade horizontal. Key lock on panel prevents accidental changes in attenuator setting.

DETECTOR

Characteristics: RMS with true (linear) integration. Choice of nine integration periods: ⅛, ¼, ½, 1, 2, 4, 8, 16 and 32 seconds.
Linearity: ±0.5 dB deviation from best straight-line fit over the top 50 dB of display range for any channel; ±1 dB over entire 60-dB range.

Sampling: Time between samples depends upon integration period selected. Sampling rate is swept over a range of about 1.8:1 during integration period to minimize coherence effects. 1024 samples are taken during integration periods of 1 to 32 seconds. Below 1-second integration period, the quantity of samples is reduced, in proportion to the integration period, to a minimum of 128.
Crest-Factor Capacity: 10 dB at full scale, increasing below full scale. Repeatability is better than 1 dB (one-σ limit) for tone burst with duty factor of 1/100 (equivalent to crest factor of approximately 23 dB) when rms levels are less than 13 dB below full scale.
Memory Duration: Unlimited while power is on.

OUTPUTS

Analog Output: Detected level output (Y axis) is linear in dB for a range in voltage of 0 to +1V ±10%, corresponding to 0 to 60 dB. Channel-number (X axis) data are linear with 0 to 1-V nominal output swing. Adjustable to 1-V swing, corresponding to quantity of output channels ranging from 10 to 45. Channels are designated by ANSI Standard Band Numbers. Overload in any channel is indicated by a "jitter" superimposed on the "level" voltage for that channel.
Digital Output: Levels in dB from 0 to 159 dB (in 0.25-dB steps) are represented by five BCD digits. Band number is reported by two BCD digits. Logic is standard 5-V TTL (positive true) for both level and band number. Overload in any channel is indicated by presence of an 8 or 9 as the most significant digit in the level indication corresponding to the channel number.
Display: Five neon readout tubes display band level in dB. Two neon readout tubes display standard band numbers (per ANSI S1.6 and S1.11).
Calibration: Full-scale and zero-level self calibration provided in two auxiliary channels. Front-panel controls allow a calibration factor to be added to digital output; full-scale indication is adjustable from 60 to 159 dB in 1 dB steps.

GENERAL

Accessories: Synchronizing and control signals provided for CRT display, automatic recorders, scanners, data printers, and computers. Interfaces specifically designed for GR 1522 DC Recorder, GR 1921-P1 Storage Display Unit, Houston Instruments 6400-024-series plotters, and Mohawk Data Sciences model 800 High-Speed Printer. 1925-9670 Transmission Record Sheets, thin mylar sheets, same size and with same scale as 1925 display window; used to record position of dots in window with grease pencil or other marker; attaches to window with self-contained adhesive strip.
Programmability: All panel-control functions except output display rate are programmable by contact closures or solid-state switches to ground.
Power Required: 100 to 125 or 200 to 250 V, 50 to 60 Hz, 135 W.
Mounting: Rack or bench (mounted in single metal cabinet).
Dimensions (width x height x depth): Bench, 19½ × 19 × 20 in. (495 × 485 × 510 mm); rack, 19 × 17½ × 16 in. (485 × 445 × 410 mm).
Weight: Bench, 95 lb (44 kg) net, 190 lb (87 kg) shipping; rack, 80 lb (37 kg) net, 120 lb (55 kg) shipping.

Catalog Number						
With Attenuator		Without Attenuator				
Bench	Rack	Bench	Rack	Description		
				1921 Real-Time Analyzer One-Third-Octave Bands		
1921-9700	1921-9701	1921-9708	1921-9709	25 Hz to 20 kHz	$9275.00	$9825.00
1921-9702	1921-9703	1921-9710	1921-9711	12.5 Hz to 10 kHz	9395.00	8005.00
1921-9704	1921-9705	1921-9712	1921-9713	3.15 Hz to 2.5 kHz	9455.00	9105.00
1921-9706	1921-9707	1921-9714	1921-1915	100 Hz to 80 kHz	9225.00	9975.00

Description	
1925-9670 Transmission Record Sheets, pack of ten	
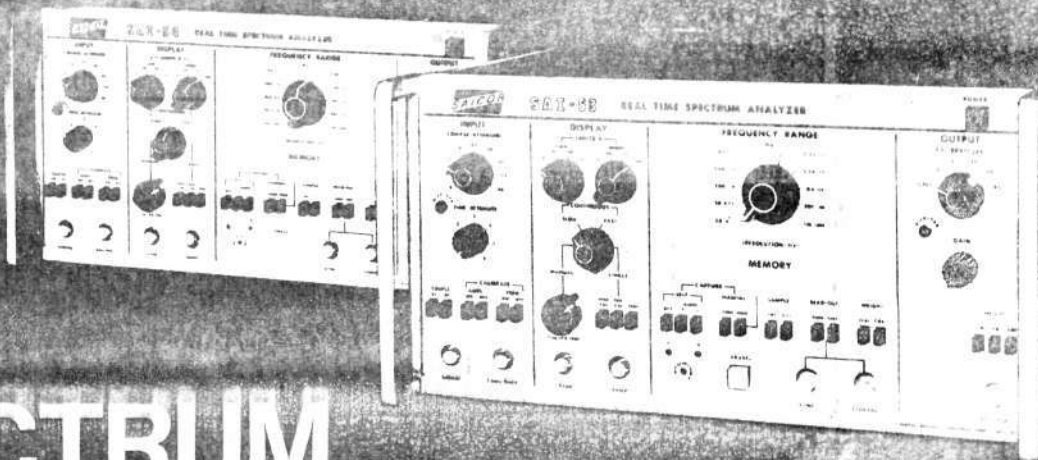
SPECTRUM ANALYZERS

SAICOR

SPECTRUM ANALYZER/ DIGITAL INTEGRATORS

Df-20

INPUT

	SAI-51	SAI-52	SAI-53	SAI-54
Impedance:	50 KΩ	50 KΩ (50Ω on 1 MHz scale)	50 KΩ	50 KΩ
Attenuation:	Coarse attenuation in 6 db steps from 0-48 db. Accuracy of ±.2 db. Fine attenuation 0-6 db (continuous). Accuracy of ±.5 db. Overload light indicates when the range of the input A/D convertor is exceeded.			
Ten Frequency Scales:	0-20 Hz, 0-50 Hz, 0-200 Hz, 0-500 Hz, 0-1 KHz, 0-2 KHz, 0-5 KHz, 0-10 KHz, 0-20 KHz, 0-1 MHz.			
3 db Resolution: Flat Weighting Cosine Weighting	200 lines	400 lines Number of lines reduced to two-thirds of the above	200 lines	400 lines
Input A/D Convertor (Sampling Rate)	Nine Bit Resolution. Conversion rate in internal sampling is set at 3 times maximum frequency of frequency range switch. On external sampling the rate is controlled by applying an external pulse train (T²L compatible pulse) at the desired sampling rate.			
Dynamic Range:	The full scale to minimum detectable signal is 50 db.			
Noise Level:	With no signal applied the noise level is 54 db below full scale.			
Sensitivity:	The minimum full scale input signal level is 100 mv rms (sine wave referred). The maximum full scale input is 50 v rms.			
Calibration:	In "ampl" calibrate a sine wave is inserted at mid-frequency, producing a full scale 5 V output spectral line with zero input attenuation. Ten equally spaced frequency markers are provided on all scales.			
Coupling:	AC or DC coupling. AC 3 db corner at 1 Hz.			

DISPLAY MODES

	SAI-51	SAI-52	SAI-53	SAI-54
Fast: (oscilloscopes)	40 msec	160 msec	40 msec	160 msec
Slow: (recorders)	8 sec	16 sec	8 sec	16 sec
Single: (Plot)	80 sec	192 sec	80 sec	192 sec
Manual:	The analysis filter is controlled by a 10 turn potentiometer. (ie. wave analyzer)			
High-Low Limits:	Independent control of high and low limits are provided in 25% increments allowing for a proportional reduction in the analysis time and number of frequency components analyzed. Operable only at the analyzer output of all units.			

MEMORY

Capture:	Self and manual transient capture modes are available. The self mode allows the automatic capture of a transient when this signal exceeds a preset adjustable threshold. Manual capture is accomplished by depressing the "hold" pushbutton or inserting a TTL logic pulse into the appropriate rear panel BNC.	
Erase:	Memory contents are cleared by depressing the erase pushbutton or inserting a TTL logic pulse into the rear panel BNC provided.	
Read Out:	Memory contents are available for viewing and read-out at two rates (peak voltage level is 1 volt). The readout times for the entire memory are:	

	SAI-51	SAI-52	SAI-53	SAI-54
Fast:	200 usec	400 usec	200 usec	400 usec
Slow:	120 msec	480 msec	120 msec	480 msec

Weighting:	Data in storage is unmodified (rectangular window) inflat mode. In cosine mode data is modified by a trigonometric function consisting of a cosine curve on a pedestal (Hanning window).

OUTPUT

Frequency Response (Flatness)	±1 db for all analysis ranges
Linearity of Spectrum Output	±½% of full scale or ±1 db whichever is greater
Frequency Linearity	±.5% of the full analysis range
Weighting Analyzer:	Linear, logarithmic and square law spectrum outputs. All modes scaled to a +5 volt maximum output.
Integrator:	Linear, logarithmic and square logarithmic weighting.
Gain Vernier:	A Vernier gain control provides 20 db of gain at the analyzer output.

Calibrate:	*(right columns, SAI-53/SAI-54)* A six position rotary switch provides calibration markers (D.C. levels) at 10 db increments. 0 db corresponds to 5 volts.
	(left columns, SAI-51/SAI-52) A six position rotary switch provides calibration markers (D.C. levels) at 10 db increments at the integrator output. 0 db corresponds to +5 volts.

INTEGRATION

Sums per Bin:	8, 16, 32, 64, 128, 256, 512 or continuous averaging. Normalization to 5V full scale.
Mode: Int.	Ensemble averaging is providing for non-redundant spectra.
Peak	A scan to scan spectral comparison yields the peak spectrum over the selected number of sums per bin.
Start-Stop-Resume:	Depressing the resume pushbutton causes a repeat of the processing cycle by adding to the existing memory contents. Depressing the start pushbutton erases the memory and begins a new processing cycle. May also be controlled remotely.
Power:	115 volts ±10%, 220 volts ±10% switch selectable, 50 to 400 Hz, 100 watts.
Size:	All units 8¾" high, 17" wide, 22¼" deep.
Weight:	All units approximately 55 lbs.

3721A

Description

Model 3721A Correlator is an all-digital, dc-to-250 kHz signal analyzer which combines four major measurement capabilities in one instrument. It measures autocorrelation, crosscorrelation, probability distributions, and signal averaging (signal recovery), the process of recovering the waveshape of repetitive signals buried in noise (described, with reference to the Model 5480A Signal Analyzer, on page 42). All results are displayed on built-in CRT.

In general, using the 3721A Correlator is similar to using an oscilloscope. Essentially an "on-line" instrument, it can easily be carried from place to place, yet has the flexibility of much larger data processing systems . . . for example, a selection of averaging time constants from a few milliseconds to many *days*. With the 3721A Correlator comes the ability to *observe* statistical behavior in real time, and to monitor changing phenomena continuously.

The computed function is displayed using 100 points: however, if more resolution is required in correlation measurements, Option series 01 provides additional delay in batches of 100 points, up to a maximum of 900 points. This pre-computational delay gives an effective resolution of 1 point in 1000 over a selected portion of the display.

The major axis of the display is scaled five points to each centimeter and is calibrated in time per millimeter: this applies to all displays other than probability, for which the horizontal axis is calibrated in volts per centimeter. (Note that for correlation functions the horizontal axis represents time *shift* between input signals rather than real time.) The time per millimeter can be switched from 1 μs to 1 second: other, intermediate, sweep rates may be obtained using an external timebase (the time/mm can be increased without limit).

Df-22

Being a digital instrument, the Correlator is easily interfaced with a computer: Option 020 provides interface hardware for reading out displayed data in 16 bit parallel binary form to any computer in the Hewlett-Packard range. Analog outputs are provided, as standard features, for both X-Y recorder and external oscilloscope.

Digital Averaging

Correlation, signal recovery and probability measurements are all processes in which the end result is the average of many samples. In the Model 3721A Correlator averaging is performed by two methods: SUMMATION and EXPONENTIAL, one or the other being selected by a front panel switch. In the summation mode, the computed function is averaged by summing N samples and then dividing the total by N: N is selectable (front panel control) from 2^7 to 2^{17}. Summation averaging anticipates the number of samples contributing to the computed function's final value, and is therefore a process of pre-established length: it is particularly useful for the analysis of a limited quantity of data.

The second averaging mode, exponential averaging, is a continuous filtering process which forgets old information and thus follows changing phenomena. If A_{p-1} is the current value of the running average and a new sample I_p arrives, the new average would be $A_p = A_{p-1} + (I_p - A_{p-1})/N$, where N is a number selectable from 2^7 to 2^{17} in binary steps. This running average algorithm is the digital equivalent of an RC smoothing filter, but with greater stability and flexibility. *Stable* because it is not subject to the drift normally associated with long time constant analog circuits, and *flexible* because changing of the time constant entails not a change of physical components, but a changed divisor, N, in the averaging algorithm. Digital averaging has the

added advantage that it makes possible very long time constants, and hence low frequency analysis, without physically large components.

The easily variable time constant is used with great effect to provide a *quick-look* facility. A long averaging time constant, essential for accurate statistical measurements, normally means a long wait before the computed function arrives at its final value . . . and hence the possibility of an abortive experiment being discovered only after a lengthy time interval. The quick-look facility in the 3721A, however, gives an immediate approximation to the final value, regardless of the length of time constant selected; and the approximation is progressively refined as the experiment proceeds.

Specifications

Input Characteristics

Two separate input channels, A and B, with identical amplifiers.

Bandwidth: dc to 250 kHz nominal. Lower cut-off frequency selectable, dc or 1 Hz.

Input range: accepts signals from 40 mV rms to 4 V rms over six ranges.

Analog-to-digital conversion: fine quantizer; 7 bits. Coarse quantizer (feeds delayed channel); 3 bits. Coarse quantizer linearized by internally-generated wideband noise (dither).

Overload: maximum permissible voltage at input; dc coupled 120 V peak, ac coupled 400 V = dc + peak ac.

Input impedance: nominally 100 pF to ground, shunted by 1 MΩ.

Correlation Mode

Computes the following functions:
Autocorrelation of A input.
Autocorrelation of B input.
Crosscorrelation of A and B inputs, A delayed.
Crosscorrelation of A and B inputs, B delayed.
Simultaneous computation and display of 100 values of auto or crosscorrelation function. Display sensitivity indicated directly in V^2/cm on illuminated panel. Non-destructive readout; computed function can be displayed for an unlimited period without deterioration. (Non-permanent storage; data cleared on switch-off.)

Timescale: (time/mm = delay increment Δt) 1 μs to 1 second (total delay span 100 μs to 100 seconds) in 1, 3.33, 10 sequence, plus external clock; minimum increment 1 μs (1 MHz), no upper limit.

Delay offset: option series 01 provides delay offset (precomputation delay) facility. Without offset, first point on display represents zero delay; with offset, delay represented by first point is selectable from 100 Δt to 900 Δt in multiples of 100 Δt.

Display sensitivity: 5 x 10^{-6} V^2/cm to 5 V^2/cm. Calibration automatically displayed by illuminated panel.

Vertical resolution: depends on display sensitivity. Minimum resolution is 25 levels/cm. Interpolation facility connects points on display.

Averaging: two modes are provided: Summation (true averaging) and Exponential.

1. Summation Mode
Computation automatically stopped after N process cycles, at which time each point on the display represents the average of N products. N is selectable from 128 to 128 x 1024 (2^7 to 2^{17} in binary steps). Display calibration automatically normalized for all values of N. Summation time indicated by illuminated panel.

2. Exponential Mode
Digital equivalent of RC averaging, with time constant selectable from 36 ms to over 10^1 seconds. Approximate time constant indicated by illuminated panel. Display correctly calibrated at all times during the averaging process.

Signal Recovery Mode (Channel B Only)

Detects coherence in repeated events, when each event is marked by a synchronizing pulse. After each sync pulse, a series of 100 samples of channel B input is taken, and corresponding samples from each series are averaged. The 100 averaged samples are displayed simultaneously. Display sensitivity is indicated directly in V/cm on illuminated panel.

Synchronization: an averaging sweep is initiated either by a pulse (TRIGGER) from an external source (EXT) or, in internally triggered mode (INT), by a pulse derived from the internal clock. In the INT mode, the start of each sweep is marked by an output pulse (STIMULUS) used to synchronize some external event.

Trigger input: ac coupled. Averaging sweep initiated by negative-going edge; minimum swing 5 volts, maximum 12 volts; maximum fall time 2 μs; minimum pulse width 0.5 μs; maximum dc voltage 200 volts.

Stimulus output: negative-going pulse at start of averaging sweep, +12 V to 0 V, duration >0.5 μs; interval between stimulus output pulses equals 100 x time/mm, plus up to 270 μs.

Timescale: (time/mm = interval between samples) 1 μs to 1 second (total display width 100 μs to 100 seconds) in 1, 3.33, 10 sequence with internal clock. Other intervals (hence other display widths) with external clock; minimum interval 1 μs (1 MHz), no upper limit.

Display sensitivity: 50 μV/cm to 1 V/cm. Calibration automatically displayed by illuminated panel.

Vertical resolution: depends on display sensitivity. Minimum resolution is 25 levels/cm. Interpolation facility connects points on display.

Averaging: two modes are provided: Summation (true averaging) and Exponential.

1. Summation Mode
Process automatically stopped after N averaging sweeps, at which time each point on the display represents the average of N samples of the input, taken at a particular displacement from the sync pulse. N is selectable from 128 to 128 x 1024 (2^7 to 2^{17} in binary steps). Summation time indicated by illuminated panel.

2. Exponential Mode
Digital equivalent of RC averaging, with time constant selectable from 36 ms to over 10^1 seconds. Approximate time constant indicated by illuminated panel.

Probability Mode (Channel A Only)

Displays either (1) amplitude probability density function (pdf) or (2) integral of the pdf of channel A input. Signal amplitude represented by horizontal displacement on display, with zero volts at center; vertical displacement represents amplitude probability.

Display sensitivity: horizontal sensitivity 0.05 V/cm to 2 V/cm in 5, 10, 20 sequence.

Horizontal resolution: 100 discrete levels in 10 cm wide display = 10 levels/cm.

Four instruments in one

Mode 3721A

Vertical resolution: 256 discrete levels in 8 cm high display = 32 levels/cm.

Vertical scaling: depends on averaging method used (summation or exponential).

1. Summation Averaging

Process automatically stopped by the first point to reach 8 cm displacement from the baseline. In the pdf mode, 8 cm vertical displacement represents approximately N occurrences of a particular signal level, N being selectable from 128 to 131,072 (2^7 to 2^{17} in binary steps). Area under pdf curve may be obtained by counting cycles of process clock.

2. Exponential Averaging

Continuous updating of display, with time constant as given for correlation and signal recovery mode.

Sampling rate: 1 Hz to 3 kHz in 1, 3, 10 sequence with internal clock. Other sampling rates with external clock; maximum frequency 3 kHz, no lower frequency limit.

Interfacing

X-Y recorder: separate analog outputs corresponding to horizontal and vertical co-ordinates of the CRT display.

X drive: nominal 12.5 V staircase, 270 ms dwell per step. Alternative dwell 1.35 seconds.

Y drive: nominal 1.25 V for each centimeter deflection on 3721A CRT display.

Pen control: 2 modes controlled by toggle switch on rear panel.

  a. Pen lowered for entire sweep.

  b. Pen plots series of 100 points per sweep.

Pen lift signal: short-circuit to ground for pen down. Maximum sink current 150 mA. In the pen-up condition, voltage from recorder must not exceed +40 V.

Recorder calibration: ZERO on DISPLAY/CAL switch puts pen to center of paper. CAL puts pen to lower left. Depressing the RECORD pushbutton gives a single sweep output to the X-Y recorder.

Oscilloscope: separate analog outputs corresponding to the horizontal and vertical co-ordinates of the CRT display.

Noise Generator Model 3722A: control of the Correlator from the Model 3722A Noise Generator. The gate signal from the 3722A is used to set the Correlator into RUN state. On termination of the gate signal, Correlator will go into HOLD state.

Gate Signal 3722A*: +1.5 V when gate open sets Correlator into RUN state; on rising to +12.5 V (gate closed), sets Correlator into HOLD state.

Digital computer: Option 020 provides interface hardware (buffer card) for reading out displayed data to any Hewlett-Packard digital computer.

Data output*: signals containing VERTICAL ordinate information transmitted to the computer. The 100 displayed points are scanned in sequence on command from the computer. Each point is represented by 16 bits parallel binary information comprising 10 bits amplitude data, 2 bits sign, 2 bits range factor, and 2 bits command information, one denoting instrument in HOLD state and the other "time constant reached" condition. Ordinates are presented, to the computer, for a period of approximately 130 μs and a *data ready* signal marks the changeover from one to the next. The data ready signal can be used to initiate a computer interrupt.

Df-24

Computer commands*

  Run: signal from computer which sets Correlator into RUN state.

  Hold: signal from computer which sets Correlator into HOLD state.

  Reset: signal from computer which sets Correlator into RESET state.

  Data: signal from computer which commands Correlator to output a series of 100 data words, if Correlator is in HOLD state.

Clock*

  Internal clock: all timing signals derived from crystal-controlled oscillator: stability 40 ppm over specified ambient temperature range. Internal clock output: train of negative-going pulses, +12 V to 0 V, >0.5 μs wide, period as indicated by TIMESCALE switch.

  External clock: maximum frequency 1 MHz. Negative-going level change, minimum transition −5.5 V to +2.8 V, initiates clock pulse. Minimum dwell at lower level 0.5 μs. Maximum permissible levels +13.5 V to −8 V.

  Process clock: 135 μs wide negative-going pulse. Normally 0 V, rises to −12 V at start of each process cycle and returns to 0 V after 135 μs.

Remote Control and Indication*

Control: remote control inputs for RUN, HOLD and RESET functions are connected to DATA INTERFACE socket on rear panel. Command represented by negative-going level change, minimum transition −5.5 V to −2.8 V. Minimum dwell at lower level 1.5 μs. Maximum permissible levels −13.5 V to −8 V.

Indication: remote indication of Correlator RUN, HOLD or RESET states is available at the DATA INTERFACE socket on rear panel. A condition will be indicated as true when signal is at 0 V.

Display

Mono-accelerator tube, 3 kV accelerating potential; aluminized P31 phosphor; etched safety glass faceplate reduces glare, 8 x 10 cm parallax-free internal graticule marked in cm squares, 2 mm sub-divisions on major axes.

General

Ambient temperature range: 0° to 50°C.

Power: 115 or 230 V ±10%, 50 to 400 Hz, 150 W.

Dimensions: 16¾" wide, 10¼" high, 18¾" deep overall (426 x 272 x 476 mm).

Weight: 45 lb (20.5 kg) net.

Accessories furnished: detachable power cord, rack mounting kit, trimming tool, circuit extender boards (2 supplied), special-purpose coax extender lead, 50-contact male cable plug.

Price: Model 3721A $8300 ($7600 at factory in Scotland).

Options

Delay offset: option series 01. Full details to be announced.

Data interface: option series 02. Option 020 Correlator with interface for data output to computer.

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* Denotes signals specified as follows:

Correlator output signals

TRUE or low state −1 V to −1.5 V, sinking up to 12 mA.

FALSE or high state +12 V, output impedance 12 kΩ.

Correlator input signals

TRUE or low state −1 V to +2.8 V.

FALSE or high state ±5.5 V to 12 V.

0.001 Hz to 99.9 kHz
## HIGH-PASS, LOW-PASS,
BAND-PASS, BAND-REJECT
VARIABLE FILTER
models 3340 and 3342

- *All silicon solid-state*
- *Frequency range:* 0.001 to 99.9 kHz
- *Frequency accuracy:* ±2%
- *Pass Band Gain:* 0db or 20db
- *Attenuation slope:* 48db/oct. (each channel)
- *Battery operation*
- *Maximum attenuation:* 80db
- *Floating (ungrounded) operation*

MODEL 3340 ▶

MODEL 3342 ▼

The Krohn-Hite Model 3300 Series are all silicon, solid-state, variable electronic Filters that are digitally tuned over the range from 0.001 Hz to 99.9 kHz. The Models 3320 (single channel) and 3322 (dual channel) provide 24db per octave attenuation slopes, and the Models 3340 (single channel) and 3342 (dual channel) have slopes of 48db per octave. Each channel can be operated in either the High-Pass or Low-Pass mode providing versatility never before available over this frequency range. Refer to separate bulletin on the Models 3320 and 3322 for detailed specifications. When the two channels in the Model 3342 are operated in the same mode, set at the same cutoff frequency, and cascaded, an attenuation slope of 96db per octave is obtained.

The frequency response characteristic of the Models 3340 and 3342 is an eighth-order Butterworth with maximal flatness for cleanest filtering in the frequency domain. For pulse or transient signal filtering, a front panel switch is provided to change the frequency response to Low Q, optimum for
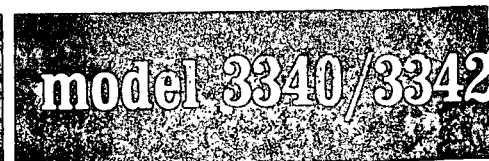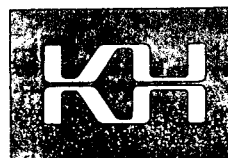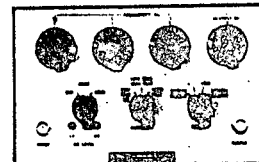
transient-free filtering (see photo). Digital tuning permits cutoff frequency calibration accuracy of ±2% and excellent resettability enabling good repeatability of filter characteristics.

Either 0db or 20db of passband gain is provided with a small increase in output noise. This improves the signal to noise ratio. The 10 megohm input impedance and the 50 ohm output impedance minimizes loading, and improves high-frequency performance. Battery operation makes these Filters ideal where it is necessary to be completely isolated from the line. All Filters are designed to operate from line or batteries. Filters initially ordered without batteries can be easily converted to battery operation by purchasing special batteries from Krohn-Hite at a later date.

These filters are designed primarily for applications in the ultra-low frequency range. Their excellent cutoff frequency accuracy and resettability, coupled with stable dc output level and low distortion, results in a significant contribution to filter technology.

NORMALIZED FREQUENCY
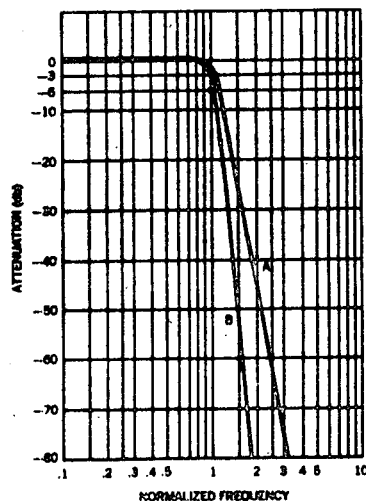
Curve A: Single channel, Low-Pass response (48 db/octave).   **Curve B: Dual channel cascaded Low-Pass response (96 db/octave).**
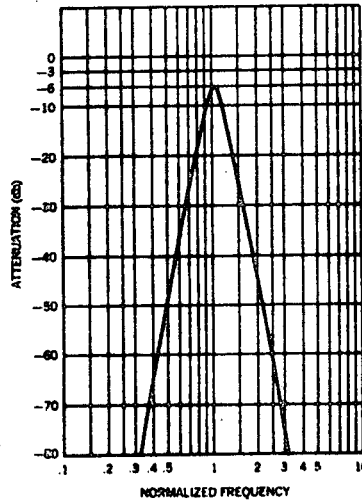
NORMALIZED FREQUENCY

MODEL 3342: Minimum bandwidth response in Band-Pass operation.
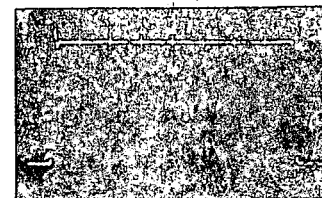
Response (in Low-Pass mode) to 1 Hz square wave, with cut-off at 1 kHz in Butterworth position.
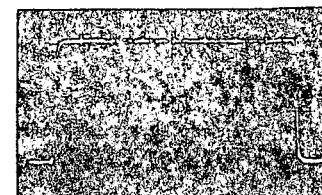
Response to same square wave in Low Q position.

FILTER

model 3340/3342

SPECIFICATIONS

Function:

MODEL 3340 (single channel):
HIGH-PASS — 48 db per octave attenuation slope.
LOW-PASS — 48 db per octave attenuation slope.

MODEL 3342 (dual channel):
Channels cascaded.
HIGH-PASS — 96 db per octave attenuation slope.
LOW-PASS — 96 db per octave attenuation slope.
BAND-PASS — 48 db per octave attenuation slopes.
Channels connected in parallel.
BAND-REJECT — 48 db per octave slopes.

Cutoff Frequency Range:

0.001 Hz to 99.9 kHz

BAND	MULTIPLIER	FREQUENCY (Hz)	RESOLUTION (Hz)
1	0.001	0.001-0.999	0.001
2	0.01	1-9.99	0.01
3	0.1	10-99.9	0.1
4	1	100-999	1
5	10	1,000-9,990	10
6	100	10,000-99,900	100

Frequency control (each channel): Three rotary decade switches for frequency digits and a six position rotary multiplier switch.

Cutoff frequency calibration accuracy: ±2% from 0.05 Hz to 9.99 kHz (less accurate in High-Pass mode at 0.001 Hz), ±10% at 0.001 Hz (less accurate in High-Pass mode at 0.001 Hz), ±10% from 10 kHz to 99.9 kHz (Band 6). Relative to pass-band level, the filter output is down 3 db at cutoff in the Butterworth (maximally flat) position and approximately 18.5 db down when operated as a Low-Pass filter in Low Q (transient free) position.

Bandwidth:

LOW-PASS MODE: DC to cutoff frequency setting within the range from 0.001 Hz to 99.9 kHz.

HIGH-PASS MODE: Cutoff frequency setting between the range of 0.001 Hz and 99.9 kHz to the upper 3 db point of approximately 1 MHz.

BAND-PASS OPERATION (Model 3342): Variable within the cutoff frequency limits of 0.001 Hz to 99.9 kHz. For minimum bandwidth, the high-pass and low-pass cutoff frequencies are set equal. This produces an insertion loss of 6 db, with the −3 db points at 0.9 and 1.12 times the midband frequency.

BAND-REJECT OPERATION (Model 3342): Variable within the cutoff frequency limits of 0.001 Hz and 99.9 kHz. The low-pass band extends to dc. The high-pass band has its upper 3 db point at approximately 1 MHz.

Response Characteristics:

BUTTERWORTH: Maximally flat, eight pole Butterworth response for optimum performance in frequency domain.

Low Q: Eight pole damped response for transient-free time domain performance.

Attenuation Slope: Nominal 48 db per octave per channel in high-pass or low-pass modes.

Maximum Attenuation: Greater than 80 db for input frequencies to 1 MHz.

Pass-Band Gain (selected by front panel control):
0 ± .5 db or 20 ± .5 db for Bands 2 thru 5, 0 ± 1 db or 20 ± 1 db for Bands 1 and 6.

Input Characteristics:

MAXIMUM VOLTAGE: ±7 volts peak in the 0 db gain position ±0.7 volts peak in the 20 db gain position.

MAXIMUM DC COMPONENT:
LOW-PASS MODE: Combined ac plus dc should not exceed 7 volts peak in the 0 db gain position and 0.7 volts peak in the 20 db gain position.
HIGH-PASS MODE: ±100 volts.

IMPEDANCE: 10 megohms in parallel with 80 pF.

Output Characteristics:

MAXIMUM VOLTAGE: ±7 volts peak to 500 kHz decreasing to ±3 volts peak at 1 MHz, open circuit.

MAXIMUM CURRENT: ±70 ma peak to 500 kHz decreasing to 30 ma peak at 1 MHz.

IMPEDANCE: 50 ohms.

Distortion: Typically less than 0.1% over most of the range.

Hum and Noise (0 db or 20 db gain position): Less than 0.5 millivolts rms for a detector bandwidth of 100 kHz, rising to 2 millivolts rms for a detector bandwidth of 10 MHz. Band 6, High Pass mode only, 2 millivolts rms for a detector bandwidth of 100 kHz, rising to 5 millivolts rms for a detector bandwidth of 10 MHz.

Output DC Level Stability: ±1 millivolts per hour, ±1 millivolt per degree C.

Operating Temperature Range: 0° to 50°C.

Floating (ungrounded) Operation: A switch is provided on rear of chassis to disconnect signal ground from chassis.

Terminals: Front panel and rear of chassis, one BNC connector for Input, one for Output, each channel. One rear terminal for chassis ground.

Power Requirements: 105-125 or 210-250 volts, single phase, 50-400 Hz, 5 watts for Model 3340, 10 watts for Model 3342.
Internal Battery (2 required per channel). Battery will operate 10 hours without recharging.

Dimensions and Weights:

MODEL	H.	W.	D.	NET WGT.	SHIPPING WGT.
3340 (cab.)	5¼"	8⅝"	17"	16 lbs/7.3 kgs	23 lbs/11 kgs
3342 (cab.)	5¼"	16⅝"	17"	32 lbs/15 kgs	40 lbs/18 kgs
3340R (rack)	5¼"	19"	17"	19 lbs/8.6 kgs	27 lbs/12 kgs
3342R (rack)	5¼"	19"	17"	32 lbs/15 kgs	40 lbs/18 kgs

KROHN-HITE CORPORATION

FILTER

2 Hz to 200 kHz
HIGH PASS, LOW PASS
## BAND PASS, BAND REJECT
VARIABLE FILTER
model 3550
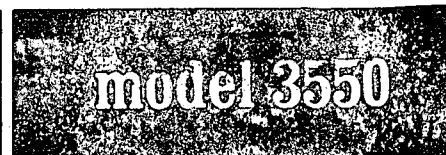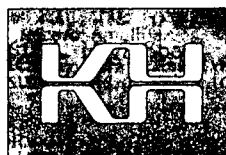
- *Frequency range:* 2 Hz to 200 kHz
- *Response characteristic:* Butterworth or Low Q
- *Calibration accuracy:* ±5%
- *Insertion loss:* 0 db
- *Attenuation slope:* 24 db per octave
- *Maximum attenuation:* 60 db
- *Hum and noise:* 200 μv
- *Bandwidth:.* 2 Hz to 3 MHz
- *Floating (ungrounded) operation*
- *Switch selectable modes*
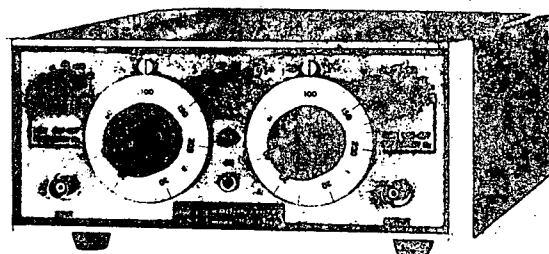
MODEL 3550

THE KROHN-HITE MODEL 3550 is a multifunction filter offering band-pass, band-reject, low-pass or high-pass operation in a single instrument. The mode of operation is selectable by means of a front panel switch. The cutoff frequency is continuously adjustable from 2 Hz to 200 kHz. In the low-pass and band-reject modes the lower 3 db point is approximately .2 Hz. In the high-pass and band-reject modes the upper 3 db point is approximately 3 MHz. The response characteristic approximates a fourth-order Butterworth with maximal flatness for optimum filtering in the frequency domain. For pulse signal filtering, a switch is provided to change the response characteristic to a damped, Low Q response for transient free filtering of pulse type signals. Band-pass gain is unity and the attenuation slope is 24 db per octave.

This filter is an outstanding value in terms of performance and economy. The high input impedance minimizes loading of circuits, while a low output impedance overcomes the load sensitivity which is a major difficulty of passive filters. The filter may be used in many applications where previously price, size, power consumption or poor transient performance have been serious limitations. Optimized frequency or time domain characteristics open up new applications where electronic filters were previously unusable.

The Model 3550 consists of independent high-pass and low-pass sections, each containing four cascaded R-C elements. Each section is switched by a front panel control to give the proper mode of operation. A highly regulated power supply eliminates any effect line transients may have.

This instrument may be used in sound and vibration measurements, sound recording, controlling the band-width of random noise test sources, suppressing interference in audio communication circuits, and numerous specialized applications.
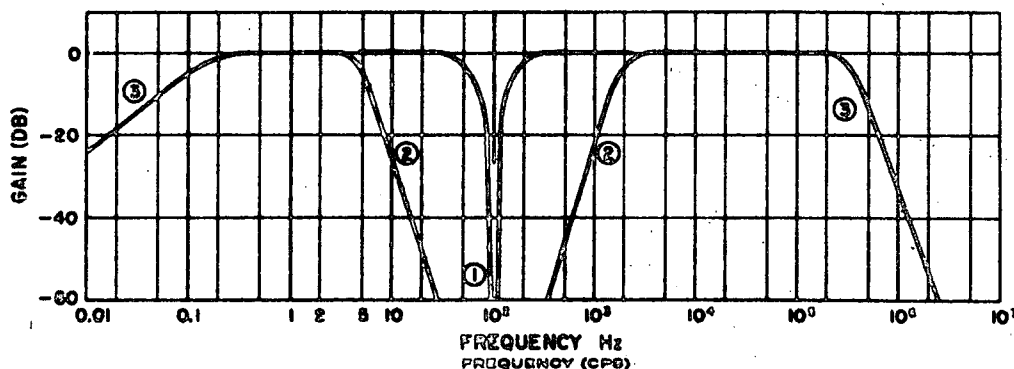
Typical filter response. (1) shows a sharp null at 100 Hz and (2) a rejection band from 5 Hz to 2 kHz as provided in the band-reject mode. (3) shows the pass-band limits in the band-reject and the high-pass modes.

FILTER

model 3550

SPECIFICATIONS

Function:

Low-pass, high-pass, band-pass, band-reject

Cutoff frequency range:

BAND	MULTIPLIER	FREQUENCY (Hz)
1	0.1	2 - 20
2	1	20 - 200
3	10	200 - 2,000
4	100	2,000 - 20,000
5	1,000	20,000 - 200,000

Frequency control:

One decade dial and 5 position multiplier switch for low-cutoff and high-cutoff functions. Effectively a 30 inch long scale for the 5 bands.

Cutoff frequency calibration accuracy:

±5% bands 1 thru 4, ±10% band 5 with "Response" switch in "max-flat" (Butterworth) position; less accurate in "Low Q" position. Relative to mid-band level, the filter output is down 3 db at cutoff in "max-flat" position, and approximately 12 db in "Low Q" position.

Bandwidth:

LOW-PASS MODE – Approximately 0.2 Hz to cutoff setting between 2.0 Hz to 200 kHz.

HIGH-PASS MODE – Cutoff setting between 2.0 Hz to 200 kHz to approximately 3 MHz.

BAND-PASS – Both cutoffs adjustable from 2.0 Hz to 200 kHz. For minimum bandwidth (Butterworth response) both cutoff frequencies are set to coincide. This produces an insertion loss of 6 db, with the 3 db points at 0.8 and 1.25 times the mid-band frequency.

BAND-REJECT – Both cutoff frequencies adjustable from 2.0 Hz to 200 kHz. Lower pass-band to approximately 0.2 Hz, higher pass-band to approximately 3 MHz. A sharp null can be obtained by setting the LOW CUTOFF FREQUENCY to about twice the null frequency, and the HIGH CUTOFF FREQUENCY to about half the null frequency, and alternately adjusting both dials for minimum response.

Response characteristics:

Choice of 4 pole Butterworth (maximally flat response) for frequency domain operation and Low Q (damped response) for transient-free time domain operation, selected by means of a switch on the rear panel.

Attenuation slope:

Nominal 24 db per octave in all modes of operation.

Insertion loss:

0 ± 1 db.

Maximum attenuation:

Greater than 60 db.

Input characteristics:

MAX VOLTAGE ±7 V peak to 2 MHz.
MAX DC COMPONENT ±100 V.
INPUT IMPEDANCE – 10 M ohms in parallel with 50 pf.

Output characteristics:

MAX VOLTAGE ±7 V peak to 2 MHz.
MAX CURRENT ±15 ma peak.
INTERNAL IMPEDANCE – approximately 50 ohms.

Hum and noise:

Less than 200 μv, except 400 μv on Band Reject mode.

Output DC level stability:

±1 mv/°C, ±1 mv/hr

Operating temperature range:

0°C to 50°C

Front panel controls:

LOW-CUTOFF FREQUENCY Hz dial and multiplier switch
HIGH-CUTOFF FREQUENCY Hz dial and multiplier switch
FUNCTION switch
Power ON switch

Rear panel controls:

RESPONSE switch
GROUND switch
DC LEVEL potentiometer

Floating (ungrounded) operation:

A switch is provided on rear of chassis to disconnect signal ground from chassis.

Terminals:

Front and rear panels, one BNC connector for INPUT, one for OUTPUT. One rear terminal for chassis grounding.

Power requirements:

105 to 125 or 210-250 volts, single phase, 50-400 Hz, 10 watts.

Dimensions and weights:

Standard bench *Model 3550* – 3½" high, 8½" wide, 13" deep; 9 lbs./4 kgs. net, 14 lbs./7 kgs. shipping.
Rack-mounting *Model 3550R* – 3½" high, 19" wide, 13" deep; 11 lbs./5 kgs. net, 16 lbs./8 kgs. shipping.

SPECIFICATIONS

MODEL 417 WIDEBAND
INSTRUMENTATION TAPE RECORDER/REPRODUCER

6½

15 ³⁄₁₆

13 ¹⁵⁄₁₆

GENERAL CHARACTERISTICS
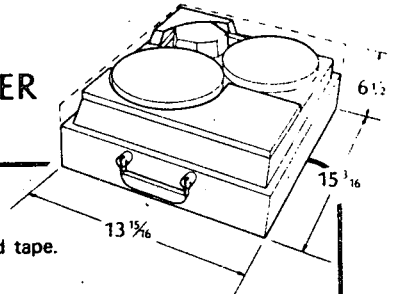
SIZE:	13-15/16 x 15-3/16 x 6-1/2 inches.
WEIGHT:	Less than 30 pounds with 8 electronic modules and tape.
TAPE SPEEDS:	3 3/4, 7 1/2, 15 ips or 7 1/2, 15, 30 ips.
TAPE DIMENSIONS:	1/2 - inch tape. Accepts 1.0 mil base tape. 7 - inch diameter reels. Cover closes with reels in place.
CONTROLS:	Pushbutton operation for OFF, RECORD, PLAY, REWIND, FAST FORWARD. Electronic modules may be intermixed to provide any combination of Direct and FM record or reproduce channels. Recorder provides either 7-track record with switchable reproduce, or 7-track reproduce. Up to 4 tracks of simultaneous record-reproduce (7 tracks optional). Meter provided for optimum direct-record level adjust and battery "state-of-charge" monitoring.
START TIME:	10 seconds or less at 30 ips from STOP to stable speed. 8 seconds or less at 15 ips from STOP to stable speed. 5 seconds or less at 7½ ips and below from STOP to stable speed.
STOP TIME:	5 seconds or less from any running speed.
REWIND AND FORWARD TIME:	5 minutes for 1,800 feet of tape.

TAPE RUNNING TIME:

TAPE SPEED (ips)	1800 feet 1.0 mil
3-3/4	90 min.
7-1/2	45 min.
15	22 min.
30	11 min.

INTERNAL POWER CONSUMPTION:	Averages 25 watts @ - 17 volts, with transport and all electronics operating at 30 ips. Internal Ni-Cd battery provides 1.0 hour operation on one charge (larger battery optional). Automatic low - voltage cutoff.
BATTERY CHARGING:	Charging time 14.hours at 120 ma (20 volts dc). BACPAC Battery Charger and Auxiliary Power Supply (Catalog No. 1020 WB) available as optional equipment. Permits Recorder operation from 115/220 volts 50 to 400 Hz. Also charges battery.

PEAK-PEAK FLUTTER IN %

MAXIMUM CUMULATIVE FLUTTER:

UPPER BAND LIMIT (HZ.)	625	1250	2500	5000	CARRIER FREQUENCY FOR FLUTTER MEASUREMENT — HZ.
SPEED (IPS)					
3-3/4	.8				6750
7-1/2		.6			13500
15			.5		27000
30				.5	54000

ENVIRONMENTAL

TEMPERATURE: 32° to 120°F operating.
-20° to 160°F non-operating

HUMIDITY: To 95% without condensation.

DIRECT RECORD/ REPRODUCE SYSTEM

FREQUENCY RESPONSE:

TAPE SPEED (ips)	FREQUENCY RESPONSE (±3 db)	SIGNAL-to-NOISE*
30	500 to 375 KHz	30 db
15	500 to 187 KHz	30 db
7-1/2	500 to 93 KHz	28 db
3-3/4	500 to 46 KHz	27 db

* rms signal to rms noise — 1000 Hz signal recorded to 1.5% total harmonic distortion. Measured per IRIG 106-63.

SIGNAL-TO-NOISE RATIO: Nominal signal level for 1.5% total harmonic distortion (1,000 Hz fundamental): Noise measurements include circuit and media noise. Measurements made with 18 db/octave attenuation bandpass filter at output of reproduce amplifier.

INPUT LEVEL: 100 mv to 10 volts rms.

OUTPUT LEVEL: 1.0 volts rms (nominal across a 75 ohm load at normal recording level).

INPUT IMPEDANCE: 1,000 ohms nominal

OUTPUT IMPEDANCE: 0.5 ohm maximum.

HARMONIC DISTORTION: 1.5% (measured at 1,000 Hz).

CROSSTALK: -35 db (below nominal signal level at 1 kHz).

FM RECORD/ REPRODUCE SYSTEM

SIGNAL CHARACTERISTICS:

TAPE SPEED (ips)	CENTER FREQUENCY (Hz)	FREQUENCY RESPONSE (Hz) (±½ db)	SIGNAL-to-NOISE*
30	225,000	0 to 100,000	35 db
15	112,500	0 to 50,000	34 db
7-1/2	56,250	0 to 25,000	33 db
3-3/4	28,125	0 to 12,500	32 db

* rms signal to rms noise. Measured per IRIG 106-60.

INPUT LEVEL: ±1.414 volts for full deviation (±30%).

OUTPUT LEVEL: ±1.414 volts peak-to-peak (nominal when loaded with 75 ohms).

HARMONIC DISTORTION: 1.5% maximum for modulation indices greater than 3, 3% for less than 3.

INPUT IMPEDANCE: 1,000 ohms nominal.

OUTPUT IMPEDANCE: 0.5 ohms maximum.

AC/DC LINEARITY: ± 1% of full scale.

TEMPERATURE STABILITY: Center frequency or output drift ≤ 0.5% per 10°C over operating temperature range.

SERVO SYSTEM

DESCRIPTION: Multiple-loop servo containing a coarse velocity-sensitive loop and a fine, high-resolution locked-phase servo. System integrated with supply and takeup reel motor control to provide overall maximum efficiency.

SPEED ACCURACY: ±0.25% at 70°F.

SERVO DRIFT: ±1.0% over operating temperature range. Special oscillator available to provide 0.1%.

Specifications are subject to change without notice.

YOUR REPRESENTATIVE IS

Specifications:

Model 5600 Portable Magnetic Tape System
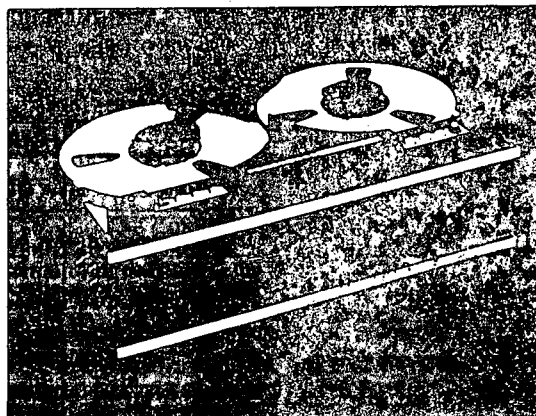
The Honeywell Model 5600 Magnetic Tape System is a full 14-channel instrumentation grade recorder which handles virtually any tape recording requirement in both laboratory and field applications.

Extensive use of aerospace technology and electronics enable true laboratory performance in a portable package weighing approximately 65 pounds. The basic recorder accommodates sixteen data cards for any combination of record/reproduce channels totaling sixteen. An auxiliary housing is available for expansion to a total of 32 data cards.

Built-in features permit easy on-the-spot conversion of tape width, power source, and recording technique to meet a variety of special requirements at remote locations. Plug-in equalizers and center frequency assemblies permit original investment to be minimized while providing added capability for future expansion. Two equalizers or center frequency assemblies are electrically switched with the rotary tape speed selector. In addition, the capability to use thin base tape on 10½ inch reels provides recording time equal to that of larger systems.

- Low mass — high performance Phase Lock Servo Drive System

- A full 1" — 14 channel recorder in a package 23" x 13" x 9"

- Universal Reel Adapters 1/4" — 1" tape, 5/16" or 3" hubs

- Seven electrically switched speeds from 15/16 to 60 ips

- Plug-in equalizers and center frequency assemblies

- Direct electronics to 300 KHz

- F.M. electronics to 40 KHz
  - Low band
  - Intermediate band
  - Wideband Group I

- Serial Digital to 600 BPI

- Choice of power from 115/230 V-48 to 420 Hz. 10 to 15 VDC or 22 to 30 VDC

A complete line of auxiliary components is available to extend the flexibility of the Model 5600, including:

- Meter Monitors

- Attenuators

- Differential Inputs

- Alternate Power Supplies

- Remote Control Units

- Auxiliary Housing

- Time Code & Search Systems

General

Size:

Portable Configuration: 23" x 13⅜" x 9"
Horizontal Rack Mounting: 15¾" panel space in 19" rack (edges of 10½" reels overhang vertical frame of rack).
Vertical Rack Mounting: 22¾" panel space in 19" rack.

Weight:

65 lbs. for seven channel direct record/reproduce configuration, excluding magnetic tape.

Input Supply: 3 available

AC: 105-129 VAC or 210-240 VAC (input voltage range field selectable) 48-420 Hz
DC: (a) 10-15 VDC
(b) 22-30 VDC

Power Consumption:

250 watts

Temperature:

Operating: 0°C to 50°C
Storage: —40°C to 70°C
Drift and other operational specifications apply with a single calibration from 10° to 35°C.

Altitude:

Operating: to 15,000 feet
Non-operating: to 50,000 feet

Humidity:

5% to 95% non-condensing

All above specifications apply to basic 16 Data Module Configuration unless otherwise noted.

Tape Transport

Basic Configurations:

Two available — ½" to 1" or ¼" to ½"
Easily field convertible between basic configurations

Tape Speeds:

60, 30, 15, 7½, 3¾, 1⅞, 15/16 ips
bi-directional and electrically selectable by rotary switch.

Hubs, Reels and Tape Width:

Reel Outside Diameter	Reel Hole Size	Tape Width
5"	5/16" NAB	¼"
7"	5/16" NAB	¼"
8"	3" NAB	¼", ½", 1"
10½"	3" NAB	¼", ½", 1"
10½"	5/16" NAB	¼"

Universal adapter accepts all of above combinations. Spacer required for ¼" reels with 3" hub. ASCII and non-standard adapters available.

Start Time: 3 seconds maximum at 60 ips.

Stop Time: 3 seconds maximum at 60 ips.

Fast Mode Speed: 200 ips for ¼" tape
150 ips minimum for ½" or 1" tape.

Static Skew:

Adjustable record and reproduce head azimuth to reduce static skew to less than 2 microseconds between outside tracks on a single 1" head stack at 60 ips.

Dynamic Skew (ITDE):

Less than · 3 microseconds between outside tracks on a single 1" head stack at 60 ips over a 10 second period. Proportionally higher at lower tape speeds.

Flutter:

Measured per IRIG 106-66. Servoed from capstan motor tachometer in record and reproduce.

Tape Speed (ips)	Bandwidth (Hz)	Cumulative Flutter % PK to PK (2 Sigma)
60	0.2 · 10,000	0.3
30	0.2 · 5,000	0.4
15	0.2 · 2,000	0.5
7½	0.2 · 1,250	0.6
3¾	0.2 · 625	0.7
1⅞	0.2 · 312	0.9
15/16	0.2 · 156	1.1

Local Control:

Pushbutton control of: POWER, DRIVE FORWARD, DRIVE REVERSE, RECORD, STOP, FAST FORWARD, and FAST REVERSE. Rotary switch selection of tape speed. Manual shorting pins to determine equalizer/speed relationship.

Remote Control:

Remote connector allows duplication of all controls with local speed switch in REMOTE position.

Remote Indicators:

End of Tape: —5 VDC at 40 ma maximum
Low tape sensors (optional): +5 VDC at 40 ma maximum

Transport Auxiliary Features:

Mechanically coupled tape footage counter.
Automatic shutdown at end of tape or tape separation.

Tape Drive System

Capstan System:

Tri-Capstan: Bi-directional and equivalent to closed loop in high frequency flutter suppression.
D.C. drive motor is directly coupled to center capstan.

Capstan Servo:

Phase lock from tape or motor tachometer. Servo system will generate standard or 2X standard IRIG constant amplitude servo frequencies. The servo system will remove a static recorded speed error of +50% and —30% at all speeds. Servo operable from tape at 15/16 ips only with 2X standard IRIG constant amplitude frequencies.

Servo Reference Frequency:

100 KHz at 60 ips crystal controlled. Proportional at other speeds per IRIG 106-66. Operable at 2X IRIG frequencies with pin jumper change on reference generator card.

Accuracy: 3 parts in 10¹ (0.03%)

Stability: 5 parts in 10¹ (0.05%) over a 25°C temperature range.

Speed Accuracy: (Over operating temperature range)

Capstan Rotational Accuracy: 0.1% when servo is operating from motor tachometer.
Tape: Within 0.15% of selected when servo is operating from motor tachometer.
Within 0.1% of recorded reference when operating from tape.

Time Displacement Error (TDE or TBE)

Servoed from tape recorded on machine with similar flutter characteristics.

Speed (ips)	TBE Microseconds (Zero to Peak)
60	1.0
30	2.0
15	3.0
7½	5.0
3¾	10.0
1⅞	12.0
15/16	15.0

Slewing Rate:

A family of attenuation curves is available upon request.

Magnetic Heads

Five Standard Configurations Available:

¼", 4 track, 0.040 wide, 0.068 C to C

¼", 7 track, 2X IRIG, 0.025" wide, 0.035 C to C, no edge track.

½", 7 track IRIG, 0.050" wide, 0.070 C to C, with 1 edge track.

½", 14 track, 2X IRIG, 0.025 wide, 0.035 C to C.

1", 14 track IRIG, 0.050 wide, 0.070 C to C, with 2 edge tracks.

Minimum Life: 1500 hours at 60 ips.

Complies with IRIG specifications for gap scatter, gap azimuth and interstack spacing.

Preamplifiers: Maximum of 16 preamplifiers, four per card.

Direct Record/Reproduce

Dynamic Characteristics:

Based on standard IRIG head configuration without an FM channel on an adjacent track, and with recommended iron oxide tapes. Capable of operation with chromium dioxide tapes.

Tape Speed (ips)	Bandwidth (Hz ± 3db)	RMS Signal/RMS Noise (db filtered)*(db unfiltered)	
60	300 - 300,000	32	30
30	150 - 150,000	32	30
15	100 - 75,000	32	30
7½	50 - 37,500	30	28
3¾	50 - 18,750	30	28
1⅞	50 - 9,300	28	26
15/16	50 - 4,700	28	26

*Measured at the output of a bandpass filter having 18 db/octave attenuation beyond bandwidth limits.

Harmonic Distortion:

Normal record level set for 1% third harmonic distortion of a 1KHz signal recorded at 60 ips.

Input Level:

0.3 vrms fixed at recorder input terminals, with gain trim adjustment.

Input Impedance:

100K ohms resistive paralleled by 100 pf, unbalanced to ground.

Output Level:

1.0 vrms fixed into 10K ohms, with gain trim adjustment.

Output Impedance:

Less than 100 ohms.

Equalization:

Mounted on plug-in equalizer cards. Each reproduce amplifier accepts two equalizers with the correct one being selected by the speed control switch.

FM Record/Reproduce (±40% deviation)

Record Amplifier:

Incorporates nine center frequencies, selected by speed switch and shorting pin for mode selection. Bias recorded.

Reproduce Amplifier:

Accepts two center frequency/filter units, selectable by speed switch. Filters convertible from flat to transient response by pin change.

Dynamic Characteristics:

Tape Speed	S/N Ratio vs. Bandwidth		
	Standard	Extended	DX
60	46 (10KHz)	44 (20KHz)	42 (40KHz)
30	45 (5KHz)	43 (10KHz)	41 (20KHz)
15	44 (2.5KHz)	43 (5KHz)	40 (10KHz)
7½	43 (1.25KHz)	41 (2.5KHz)	39 (5KHz)
3¾	42 (625 Hz)	40 (1.25KHz)	38 (2.5KHz)
1⅞	40 (312Hz)	38 (625Hz)	36 (1.25KHz)
15/16	40 (156Hz)	36 (312Hz)	34 (625Hz)

Total Harmonic Distortion:

1.5% maximum.

Linearity:

±1% of full deviation from best straight line through zero.

Drift:

1% of full deviation over 10 days and 10°C to 35°C ambient.

Input Level:

1.0 vrms fixed for ±40% deviation with zero and gain trim adjustments.

Input Impedance:

Nominal 20K ohms paralleled by 100 pf maximum unbalanced to ground.

Output Level:

1 vrms fixed into 10K ohms with zero and gain trim adjustments.

Output Impedance:

100 ohms maximum.

Voice Channel

Input:

Low impedance microphone or 600 ohm balanced input for line matching.

Input Level:

0 dbm into 600 ohm for normal record level.

Output:

600 ohm balanced for headphones or line matching.

Output Level:

+3 dbm maximum.

Distortion:

3% third harmonic distortion at 1 KHz at rated output.

Frequency Reponse:

NAB equalized 50 Hz to 15 KHz at 7½ ips. Other standard equalizers available.

Bias Oscillator:

Self contained for voice annotation during reproduce. Keyed by microphone button.

Df-33

- 2-mV/inch and 0.2-μA/inch sensitivity
- 65-inch/second writing speed
- 0.25% linearity, 0.5% accuracy
- programmable writing functions
- plug-in versatility: grounded or differential input

NEW
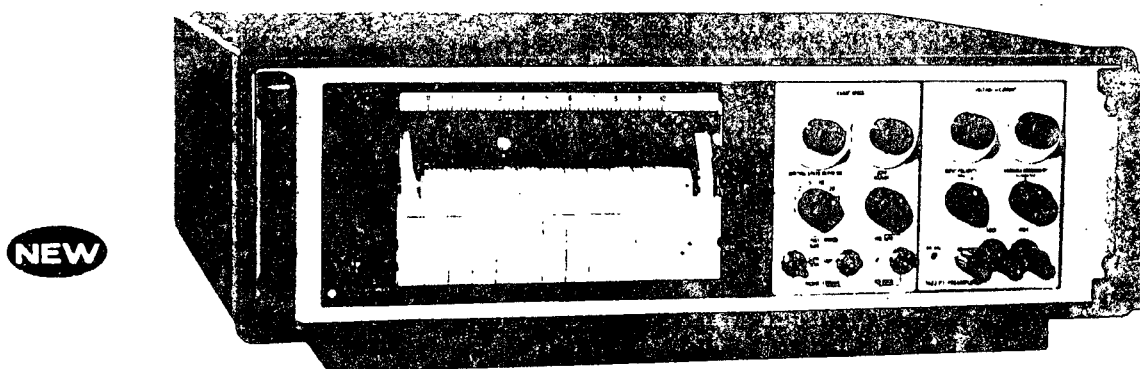
Bench model shown with 1522-P1 Preamplifier.

Imagine an automatic testing system that is programmed by its own analog recorder. As the output data are plotted, the recorder programs test conditions and measurement ranges, activates and synchronizes other recording devices, and controls its own writing functions. Triggered by timing marks printed on the chart paper, the GR 1522 DC Recorder will control companion instruments and itself, changing chart speed, rewinding the chart for overplotting, quickly advancing to a fresh graph, all the while remembering to lift the pen when not plotting. With optional limit switches, the 1522 can operate sort/select mechanisms, activate additional recorders, or alert an operator if the plotted data exceed preset high or low limits.

As an accessory to the GR 1921 Real-Time Analyzer, for example, the 1522 Recorder will plot the band levels against frequency much faster than conventional X-Y plotters. Operating synchronously with the 1921, the recorder pauses briefly as each band level is selected to allow the pen to settle, producing a neat bar graph with a standard scale factor.

The 1522 is a fine program director; it is first a superb dc recorder, combining accuracy, high sensitivity, and fast writing speed. It will plot a full-scale (5-inch) transient in under 100 ms, respond to a 200-μV or 20-nA change

with a 1-division deflection, and remain linear to within ⅛ of a division (0.25%).

The recorder accepts one of two plug-in preamplifiers. The 1522-P1 Preamplifier provides a wide range of voltage and current measurements at an economical price. The 1522-P2 Differential Preamplifier provides the same versatility with the added feature of a differential input so that measurements from ungrounded sources can be made. This plug-in offers up to 180-dB of common-mode rejection at inputs up to ±500 volts.

DESCRIPTION

The 1522 is convenient. A chart take-up reel is included, but the chart paper can feed directly out for immediate inspection and use. Controls are few and obvious; the pen, for instance, is lifted electrically by a manual switch and automatically when the chart is being positioned in either its fast-scan or slow-scan mode. For reliability, there are no gears or clutches; speed changes and control of the stepping drive motor are all done with integrated circuits.

The pen in the GR 1522 is the General Radio fastrak® marker with the fibre plastic point for clog-free operation in a disposable cartridge that eliminates messy refilling. Cartridges are easily interchanged and come in three colors.

specifications

INPUT WITH 1522-P1 PREAMPLIFIER

Ranges: Controlled by range switches, polarity switch, and continuous control with calibrated position that operates on all ranges. *DC Voltage,* 2 mV/in. to 100 V/in.; 15 ranges, 1-2-5 sequence. *DC Current,* 0.2 μA/in. to 100 mA/in.; 18 ranges, 1-2-5 sequence.

Accuracy: ⁺0.5% of full scale.

Stability: <0.01%/day drift typical in 0.2 V/in. range after warmup.

Input Resistance: 1 MΩ.

Input Isolation: >1000 MΩ dc from LOW to GROUND terminal typical at 200 V dc; 0.22 μF ac. *Voltage,* 200 V max dc or peak ac.

Common-Mode Rejection: 70 dB dc typical with 1-kΩ source impedance; 40 dB ac typical at 60 Hz.
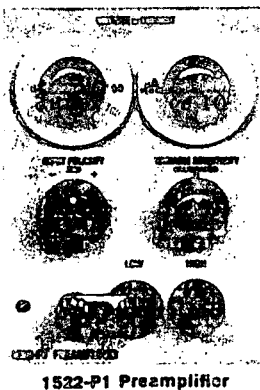
1522-P1 Preamplifier
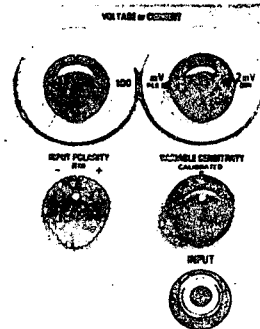
1522-P2 Differential Preamplifier

Offset and Drift: *Voltage*, Adjustable to zero. *Drift*, ±25 μV/°C from 0 to 50°C after warmup; warmup drift <0.5 mV. *Current* (bias), 0.1 nA at 25°C; doubles each rise of 11°C.

INPUT WITH 1522-P2 DIFFERENTIAL PREAMPLIFIER

Ranges: Controlled by range switches, polarity switch, and continuous control with calibrated position that operates on all ranges. *Voltage*, 2 mV/in. to 100 V/in.; 15 ranges, 1-2-5 sequence. *Current*, 0.2 μA/in. to 100 mA/in.; 18 ranges, 1-2-5 sequence.

Accuracy: ±0.5% of full scale.

Linearity: ±0.25% of full scale.

Input Resistance between HIGH and LOW terminals: *Voltage*, 1 MΩ. *Current*, 0.11 to 50.06 Ω depending on scale as follows:

Input Isolation: ≥10¹¹ Ω from GUARD terminal to ground, in parallel with <500 pF. *Voltage*, V dc or peak ac.

Common-Mode Rejection: 160 dB dc, 80 dB 60 Hz, undriven guard, typical; 180 dB ac up to 20 kHz, driven guard, typical.

Offset and Drift: *Voltage*, Adjustable to zero. *Drift*, ± (25 μV/°C from 0.005% of full scale/°C) from 0 to 75°C. *Current* (bias), 0.1 nA at 25°C; doubles each rise of 11°C.

Scale	Resistance
0.2 μA/in. to 0.2 mA/in.	$\le \dfrac{10\ \mu V/in.}{\text{scale in }\mu A/in.} + 0.06\ \Omega$
0.5 mA/in. to 10 mA/in.	$\dfrac{20\ mV/in.}{\text{scale in }mA/in.}$
20 mA/in. to 100 mA/in.	1 Ω

RECORDER RESPONSE

Fast Writing Speed: 65 in./s with <2% overshoot.

Slow Writing Speeds:	60	30	20	10	5	2	1	0.5 in./s
Servo Bandwidth (3 dB) (for ¼-in. excursions)	30	20	15	7.5	4	1.5	0.75	0.4 Hz

Linearity: ±0.25% of full scale.

Deadband: ±0.15% of full scale.

Zero Adjustment: 10-turn pot, can be set over full range.

Chart Speeds: 0.5, 1, 2, 5, 10, 20 seconds, minutes, hours per inch; 18 speeds.

Chart-Speed Synchronization: Sync outputs permit other 1522 recorders to run at identical speed or at other standard speeds in synchronization with master recorder.

Programmability: All chart control functions fully programmable and outputs provided for full system integration.

Remote-Control Functions: Require switch or solid-state closure to ground. Controls: pen lift; two event markers; 18 chart speeds; chart start, stop, forward, reverse; fast scan (2 in/s) with pen-lift; slow scan (2 in./min) with pen-lift; record command (drops pon, starts chart at selected speed); pen motion stopped in position by servo blanking.

Remote-Control Outputs: Start, stop, forward, reverse, servo-position error voltage, retransmitting potentiometer, three independent solid-state closures corresponding to lines printed on paper.

Other Outputs: Power for two additional stepper motors, power for externally controlled dc reference voltage.

Accessories Supplied: 274-NQ 3-ft double-plug patch cord, fastrak® Marker Set of 12 assorted-color pens, Event-Marker Set of 4 red, 4 black pens, 2 chart-paper rolls type 1522-9640, 2 potentiometer contacts, 2 paper cap assemblies, power cord, spare fuses.

Accessories Available: 1522-P11 Limit-Switch Set provides two adjustable limit stops; pen at limit closes reed-relay contacts with 50-V, 500-mA dc rating, 117-V, 100-mA ac rating, 210-V breakdown rating.

Power: 100 to 125 or 200 to 250 V, 50-60 Hz, 90 W.

Mechanical: Bench or rack cabinets. *Dimensions* (w x h x d): Bench, 19½ x 7 x 17 in. (495 x 180 x 435 mm); rack, 19 x 5¼ x 15¼ in. (485 x 135 x 370 mm). *Weight:* Bench, 42.5 lb. (19.5 kg) net, 58 lb (27 kg) shipping; rack, 38.5 lb (17.5 kg) net, 54 lb (24.5 kg) shipping; -P1, 1.5 lb (0.7 kg) net, 8 lb (3.7 kg) shipping; -P2, 3.25 lb (1.5 kg) net, 10 lb (4.6 kg) shipping.

Description	
1822 DC Recorder, less preamplifier	
Bench Model	
Rack Model	
1522-P1 Preamplifier	
1522-P2 Differential Preamplifier	
1522-P11 Limit-Switch Set, for two adjustable limit stops	
1522-9613 Extender Board Kit, for servicing ease	
1922-9670 Cable Set, for connection to 1921	
1522-9612 Event-Marker Set, 4 black, 4 red pens	
fastrak® Marker Sets	
1522-9446 Red, 12 pens	
1522-9447 Green, 12 pens	
1522-9448 Blue, 12 pens	
1522-9449 Assorted, 4 of each color	

Chart Paper Ideal for use with 1921 Real-Time Analyzer; 140-ft rolls with 25-dB/decade scale factors. Inch-ruled charts have 2.08-in/decade abscissas, centimeter-ruled charts have 5-cm/decade abscissas. Bands are ANSI preferred ⅓-octave.

Chart	Ordinate Scale	Abscissa Bands	Frequencies
1522-9640	*Linear	Linear, 5 div/in.	
1522-9647	*10dB/in.	30 bands—not marked	
1522-9646	12dB/in.	30 bands—not marked	
1522-9652	12dB/in.	5-34	3.15 Hz-2.5 kHz
1522-9648	12dB/in.	5-49	3.15 Hz-80 kHz
1522-9645	12dB/in.	11-40	12.59 Hz-10 kHz
1522-9644	12dB/in.	14-43	25 Hz-20 kHz
1522-9658	5dB/cm	30 bands—not marked	
1522-9656	5dB/cm	5-34	3.15 Hz-2.5 kHz
1522-9654	5dB/cm	5-49	3.15 Hz-80 kHz
1522-9657	5dB/cm	11-40	12.59 Hz-10 kHz
1522-9655	5dB/cm	14-43	25 Hz-20 kHz

* Total ordinate range is 60 dB, except for -9640 which is linear 50 div and -9647 which is 50 dB.

Input Scanners

2912A Reed Scanner is a multi-function scanner which switches guarded 3-wire inputs at speeds to 40 channels per second. Interchangeable modules plug into the mainframe:

10 channels of low level dc with the 2921A
10 channels of high level dc and ac with the 2922A
9 channels of frequency with the 2923A

Up to four modules can be installed; further input expansion is through 2920A Scanner Extenders which hold up to 10 modules each. As many as 10 extenders can be controlled by a 2912A, for 1000 channel scanning capacity.

Integrity of millivolt level signals, such as those from strain gage bridges or thermocouples, is preserved through the scanner.

System programming capability is a built-in feature of the 2912A. Diode pinboards, conveniently located behind the front panel, provide easy control of all DVM functions. Additionally, channels may be individually selected for measurement or skip-over by front panel switch selection. Groups of 10 channels may be handled in the same manner. Upper lower scan limits select the first and last channel address, and operating modes include single and continuous scan, manual scan, and single channel monitor.

Optional interface for Hewlett-Packard computer is available. Panel height of 2912A or 2920A 5¼" (113 mm).

Prices: 2912A Scanner, $3500; 2921A Low-Level DC Module, $600; 2922A DC AC Module, $600; 2923A Frequency Module, $600; 2920A Extender, $1500.

2911 Guarded Crossbar Scanner offers user choice of 600 1-wire, 300 2-wire, 200 3-wire, or 100 6-wire inputs. Permits guarded 2-wire voltage or 4-wire resistance measurements. Lower and upper scan limits selectable at front panel, with random access to any channel. Roller-mounted switch withdraws from rear for easy cabling. Maximum scanning rate is 30 channels/second. Interface for Hewlett-Packard computers available. Panel height 14" (355 mm).

Price 2911, $5600.

2901A Input Scanner/Programmer scans 25 3-wire inputs and programs all functions of associated system. May be expanded to 100 channels with 2902 Slave Units. Easy system set-up with individual quick-release input connectors and pushbutton selection of channels to be scanned. System functions and measurement delay are programmed individually for each channel with built-in pinboard. Maximum scanning rate is 12 channels/second. Panel height 7" (178 mm).

Prices: 2901A Master, $2375; 2902 Slaves (25 channels each), $1975.
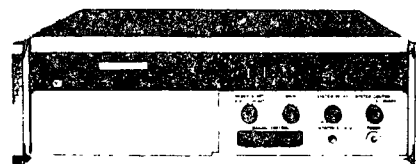
2912A
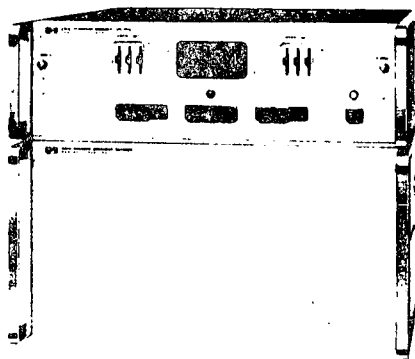
2911
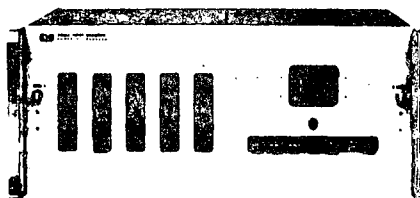
2901A

2930A Low-Level Multiplexer (page 104) is a fast, solid-state analog signal scanner that enables analog-to-digital converters to make usable low-level measurements in fast-sampling computer-automated data acquisition systems. It accepts up to 64 differential analog inputs with 20 kHz multiplex rate. Eleven input ranges programmable in binary increments to 1024 provide full scale inputs from ±10 mV to ±10 V. A choice of input filters provides rejection of undesired signal frequencies and superimposed noise; an internally-driven guard provides common mode rejection. Digital interface for analog-to-digital converters and Hewlett-Packard computers is available. Panel height 7" (178 mm).

Signal converters

2410B AC/Ohms Converter (page 214) is used in conjunction with 2401C Digital Voltmeter for measurement of ac voltages and resistances. Converter features floated, guarded input compatible with the voltmeter. Combined common mode rejection is 110 dB at 60 Hz. 2410B is fully programmable for systems use. Converter function and range information included in voltmeter display and recording outputs. Panel height 7" (178 mm).

Price: HP 2410B, $2350.

Analog-to-digital converters

2401C Integrating Digital Voltmeter (page 214) features floated and guarded input and is average-reading, yielding an effective common mode noise rejection better than 140 dB at all frequencies, including dc. All operating functions may be controlled manually or by external contact closures to ground, enabling it to be used on the bench or in systems. BCD outputs provided. Panel height 7" (178 mm).

Price: 2401C, $4300.

2402A Integrating Digital Voltmeter (page 212) combines 40 samples per second system measuring speed with 5 digit resolution. Get low-level measurements without pre-amplification. Common mode noise rejection >120 dB is provided by guarding and integration. Optional plug-in circuit cards for ac, resistance and frequency measurements yield a multimeter useful for both bench and system applications. Panel height 5¼" (133 mm).

Price: 2402A, $5450.

3450A Digital Multi-Function Meter (page 208) is basically a five-digit integrating DVM with five dc voltage ranges from 100 mV to 1000 V. Guarding and integration provide 140 dB CMR at dc, 120 dB at 60 Hz, at system speeds to 10 measurements per second. Isolated four terminal dc voltage ratio measurements are standard; options ex-

pand instrument to ac and ac ratio (true rms response), ohms and ohms ratio. Panel height 3½" (88 mm).

Price from $3150.

5610A High-Speed A to D Converter (page 99) for measurements at rates to 100 kHz of signals to ±1 V full scale (optionally ±2.5 V, ±10 V). Used in data systems employing a digital computer. Resolution is 9 bits plus sign, and aperture time with sample and hold is 50 ns. Multiplexer capability available for 8 or 16 channels with 100 kHz throughput rate. Panel height 5¼" (133 mm).

Price: $2000.

12564A High-Speed A to D Converter (page 103) is a plug-in circuit card for use with HP 2116B, 2115A and 2114B Digital Computers. Makes ±1 V or ±10 V (switch selectable) full scale single-ended measurements at rates to 50 kHz. Resolution is 9 bits plus sign, and aperture time is 17.6 µs with 2116B, 22 µs with 2115A or 2114B.

Price: 12564A, $1100.

System controllers

2114B, 2115A or 2116B Digital Computers (page 67) provide methods for flexible, sophisticated system control. Timing and sequencing of the input scanning, measuring and recording functions is controlled by the computer. It can also perform limit comparison, code conversion and output formatting otherwise accomplished by separate instruments. Data manipulation such as solving multiple variable equations on stored data or measured inputs from one or more channels is easy when the system includes one of these devices.

In high speed system applications, the computer serves additionally as a data buffer storage unit to permit accumulation of data at rates beyond that of the fastest recording devices.

Price: 2114B with 4096 word memory, $9950; 2115A with 4096 word memory, $14,500; 2116B with 8192 word memory, $24,000.

Output coupler, recorders

2547A Coupler (page 105) operates with a variety of input and output devices. As a data acquisition system element, it translates BCD information from a digital voltmeter into the correct code and format for the following digital recorders.

Price: 2547A Magnetic Tape output, $7325 to $10,050; 2547A Punched Tape output, $6275; 2547A Teleprinter output, $4500 to $7100; 2547A Typewriter output, $5100; 2547A Flexowriter output, $8825; 2547A Card punch compatible, $3800; Manual data input, $1000; Digital clock $1500 to $2100.

ADDENDUM G

FREQUENCY ANALYSERS

The following addendum was excerpted from the article "Signal Analysis Techniques for Use in Acoustic Diagnostics" by I. D. Macleod, G. Halliwell, J. C. Hale of the United Kingdom Atomic Energy Authority.

ADDENDUM G

FREQUENCY ANALYSERS

To analyse a stationary signal at a given frequency the signal is passed through a filter tuned to that frequency. The output of the filter is observed and an average value taken over a sufficiently long time to give the required degree of accuracy. This accuracy may be calculated from the standard error of the fluctuations of a signal.

$$\epsilon = \frac{1}{\sqrt{BT}}$$

where B is the bandwidth in Hz
        T is the averaging time in seconds.

The standard error as defined refers to the power spectral density or the "engergy" of the fluctuating signal. If the amplitude level of the fluctuations are considered then the amplitude errors are half that of the power error ie,

$$\epsilon_A = \frac{1}{2\sqrt{BT}}$$

The averaging time T is defined in the equation

$$\overline{a^2} = \frac{1}{T} \int_0^T a^2(t)dt \qquad \ldots\ldots (1)$$

where $\sqrt{\overline{a^2}}$ is the root mean square value of a (t). In practice this integration type averaging is often approximated to by a simple resistance-capacitance circuit of time constant RC and it is shown by Bendat and Piersol that the effective averaging time of such a time constant is given by

$$T = 2RC \qquad \ldots\ldots (2)$$

Parallel Filter Analysers

One way of constructing a frequency spectrum from the measurements of filter output described above is to have a number of filters in parallel. This is the parallel filter analyser. If an analyser of this type is to cover a wide frequency range and have fine resolution a large number of filters will be required. These analysers therefore normally have fairly course resulution, octave and $\frac{1}{3}$ octave being common though there are exceptions to this rule.

Figure 1 shows an example of spectra from such an analyzser which is used in this case to detect cavitation in a liquid sodium pump circuit. The existence of cavitation is indicated by the relatively large increase in the high frequencies. This is an ideal application for this type of analyser as cavitation is a broad band noise source and no advantage would be derived from having greater resolution.

If all the filters are permanently connected to the input signal and each to its own averaging circuit the rate at which the spectra can be determined from this type of analyser is independent of the averaging time and is determined by the physical properties of the scanning system and for a mechanical system might typically be about 1 minute. Analysers of this type with high speed scanning systems are now available and are discussed in the section on Real Time Analysers.
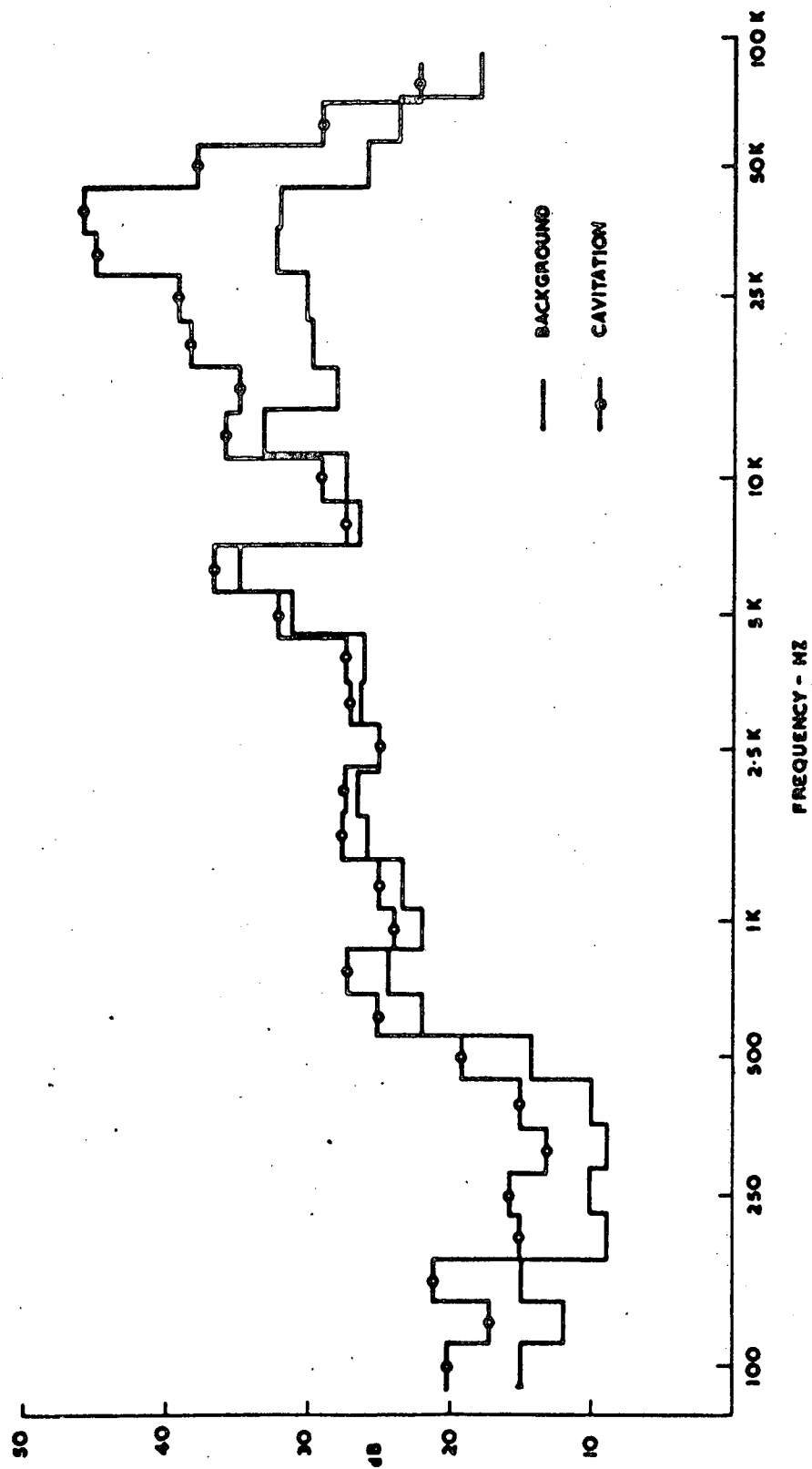
FIG. I. CAVITATION DETECTION WITH PARALLEL FILTER ANALYSER

Dg-3

If on the other hand only one averaging circuit is available and this is scanned over the filters in turn then it is necessary to dwell for at least 4 time constants on each filter and if low frequencies are involved longer scan times can result. However as the bandwidth of these analysers is usually large, octave or $\frac{1}{3}$ octave, these do not usually exceed a few minutes. The discussion of scanning rate is therefore deferred to the next section on Swept Filter Analysers where it is a more serious problem.

Swept Filter Analysers

To overcome the limitation on resolution achievable at reasonable cost in the parallel filter analyser we can turn to the swept filter analyser. Here the tuning of a single filter is varied so that it sweeps through the range of frequencies for which analysis is required. Alternatively in some systems the filter tuning remains constant and the signal frequency is translated by a varying amount so that the same result is achieved. In parallel filter analysers the bandwidth is commonly a fraction of the centre frequency This is of course a property of normal filters having the same selectivity and they will be referred to here as constant percentage bandwidth filters. The use of such filters implies a varying resolution in absolute terms through the frequency range. Since the human ear also tends to resolve sounds in this octave by octave manner this is the most appropriate type of filter for many applications particularly on the measurement of noise when subjective effects are to be considered.

However in the increasingly important field of structural vibration a different type of filter system is widely used. This is known by the self explanatory title of constant bandwidth filtering which has the virtue of offering fine resolution at high frequencies.

When using a sweeping filter analyser we consider the accuracy, resolution and averaging time as in the case of the parallel filter analyser but in addition the sweep rate has to be selected and this determines the analysis time. The maximum scan rate is one bandwidth per averaging time to prevent any blurring of the spectrum but if RC type averaging is being used it is necessary to allow 4 time constants of the filter to ensure that the output is 98% of the input, this leads to a scan rate R_s

$$R_s = \frac{B}{T} \qquad\qquad \dots\dots(3)$$

$$\left(\text{or } R_s = \frac{B}{4RC} \text{ for RC averaging}\right)$$

We also have as before

$$\epsilon = \frac{1}{\sqrt{BT}}$$

For a constant percentage bandwidth analyser using a fixed averaging time we have

$$B \propto f = kf \therefore \epsilon \propto \frac{1}{\sqrt{f}}$$

$$T = \text{const.}$$

For this analyser therefore the error is largest at the low end of the frequency range and decreases as frequency increases. Also

$$R_s = \frac{B}{T} = \frac{kf}{T}$$

ie the maximum permissible scanning rate is proportional to frequency which can be achieved by a suitable choice of frequency scale and drive unit.

This leads to a total analysis time β.

$$\beta = \int_{f_1}^{f_2} \frac{df}{R_s} = \frac{T}{k} \int_{f_1}^{f_2} \frac{df}{f} = \frac{T}{k} \ln\left(\frac{f_2}{f_1}\right) \qquad \dots\dots(4)$$

or $\qquad \frac{4RC}{k} \ln\left(\frac{f_2}{f_1}\right)$ for RC averaging $\qquad \dots\dots(5)$

In some of the more sophisticated analysers it is possible to programme the averaging time so that it changes in a stepwise manner to maintain the accuracy approximately constant ie by keeping B x T constant. This means of course that the averaging time decreases as the frequency increases and so, since the scan rate is defined by equation (3), it is possible to increase the scan rate and achieve a shorter analysis time. We have in this case

$$BT = \text{constant} = \frac{1}{\epsilon^2} \quad \text{approximately}$$

$$T = \frac{1}{\epsilon^2 B}$$

and $\qquad R_s = \frac{B}{T} = \epsilon^2 B^2 = \epsilon^2 k^2 f^2$

Analysis Time $\beta = \frac{1}{\epsilon^2 k^2} \int_{f_1}^{f_2} \frac{1}{f^2} \, df \qquad \dots\dots(6)$

$$= \frac{1}{\epsilon^2 k^2} \left[\frac{1}{f_1} - \frac{1}{f_2}\right]$$

For the constant bandwidth analyser we get by similar deduction

$$\beta = \frac{T}{B} (f_2 - f_1) \quad\quad\quad\quad \dots\dots (7)$$

These formulae enable the analysis time for a given job to be assessed. The time will depend greatly on the range selected and accuracy required and will be very long if high resolution and accuracy are required at low frequencies.

The analysis time taken by an analogue swept filter analyser to achieve a certain frequency resolution B and standard error $= \frac{1}{BT}$ can be reduced by presenting the data to the analyser from a recirculating loop running at n times the original recording speed. This has the effect of expanding the frequency spectrum and compressing the timescale. The resulting analysis time β' is given by the equation

$$\beta' = \frac{\beta}{n}$$

The saving in time is determined by the maximum gearing rates which can be achieved.

$$n_{max} = \frac{\text{maximum replay speed of recorder}}{\text{original recording speed}}$$

For tape recorders in current use, n may have values from 2 to 32 and thus analysis times can be reduced by a factor up to 32. However, this process involves copying tapes, is cumbersome and does not permit on line analysis.

We now consider examples of the application of these analyses.

Constant Percentage Bandwidth

Figure 2 shows a typical spectrum for a constant percentage bandwidth analyser. The figure represents the sound spectrum of boiling in a tank, the main peak on this spectrum at 850 Hz represents the fundamental resonance of the water volume in the tank and could be used as an indication of depth. The bandwidth is constantly increasing and so a constant power spectral density signal would have a slope of + 10 dB/decade. The boiling noise actually falls away at · 10 dB per decade and so we deduce that its power spectral density curve falls off as $\frac{1}{f^2}$

Constant Bandwidth

The ability of the constant bandwidth analyser to resolve discrete frequencies over a wide frequency range is shown in Figure 3 which shows the frequency spectra of an electrical supply line subjected to interference from thyristor controlled equipment. The filter bandwidth was 4 Hz and harmonics up to 1.6 KHz are clearly resolved.
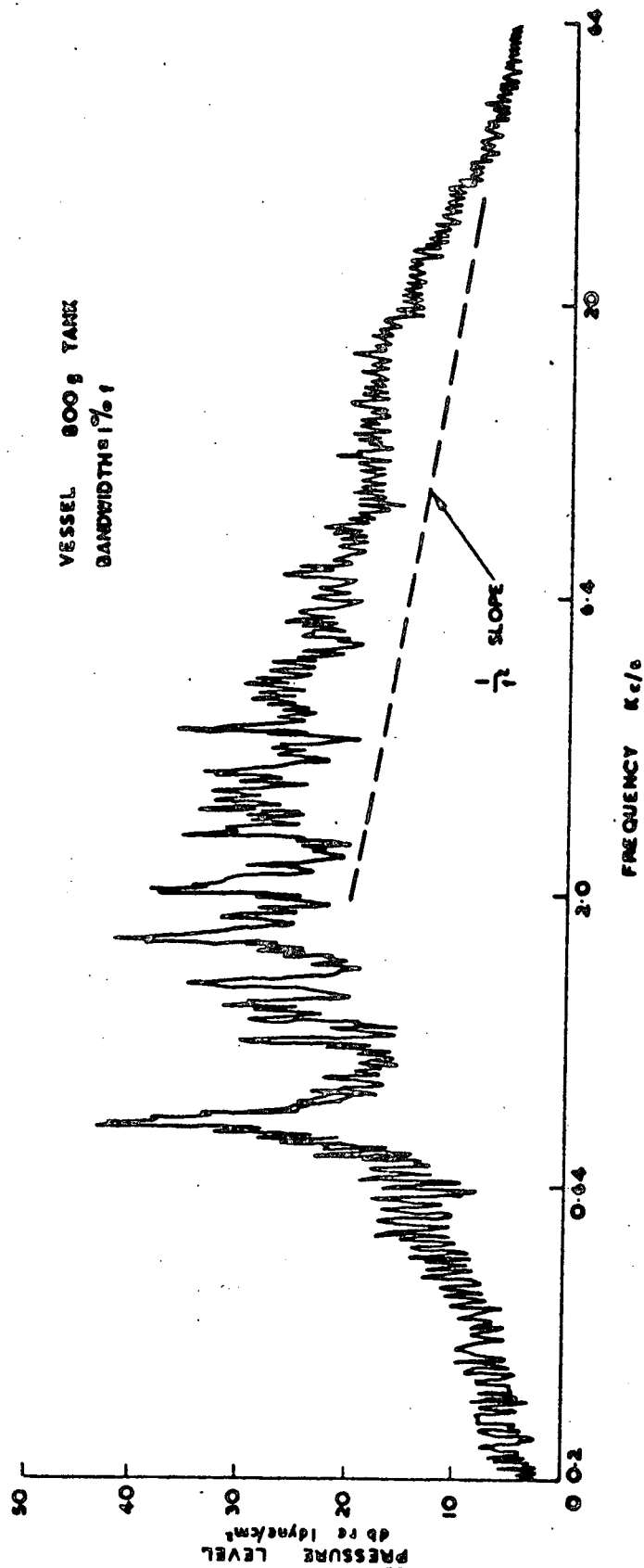
FIG. 2. SOUND PRESSURE SPECTRUM PRODUCED BY BOILING IN WATER USING SWEPT FILTER ANALISER
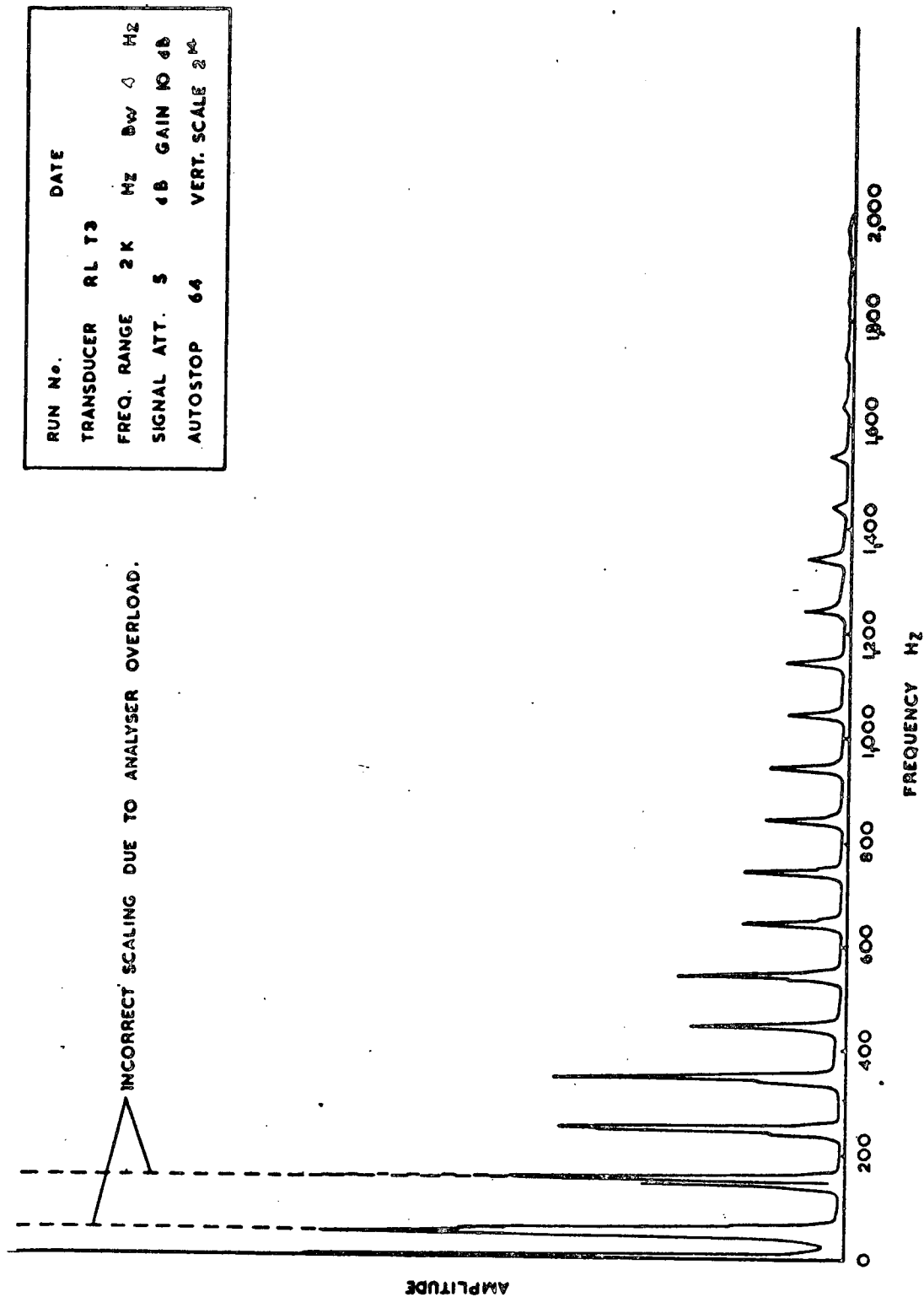
FIG. 3. HARMONICS INDUCED IN ELECTRICAL SUPPLY BY THYRISTOR CONTROLLED EQUIPMENT.

Dg-8

a 5% bandwidth analyser would have an actual bandwidth 50 Hz at all frequencies above 1 KHz and so would fail to resolve these harmonics.

In conclusion, parallel filters octave and $\frac{1}{3}$ octave analysers offer quick analysis but poor resolution especially at high frequencies. A constant bandwidth swept filter analyser gives good resolution but for wide ranges very long analysis time. The percentage bandwidth analyser offers a useful compromise between these extremes. For rapid analysis and good resolution the answer lies with the real time analysers described in the next section.

REAL TIME FREQUENCY ANALYSERS

This title has been applied to a group of analysers which have become more commonly available in the past year or two. The title is earned by their ability to produce frequency spectra many orders of magnitude more quickly than the conventional swept filter analysers, and while a "real time" analyser in the sense of producing the spectrum instantaneously is impossible these machines come within a small fraction of a second of being genuinely real time analysers.

Broadly speaking there are two classes of these analysers, parallel filter analysers of the constant percentage bandwidth type and swept filter types which basically are constant bandwidth though, for example, adaptors to convert them to $\frac{1}{3}$ octave filters are available. Following the order we have adopted for conventional analysers we will first describe the parallel filter type.
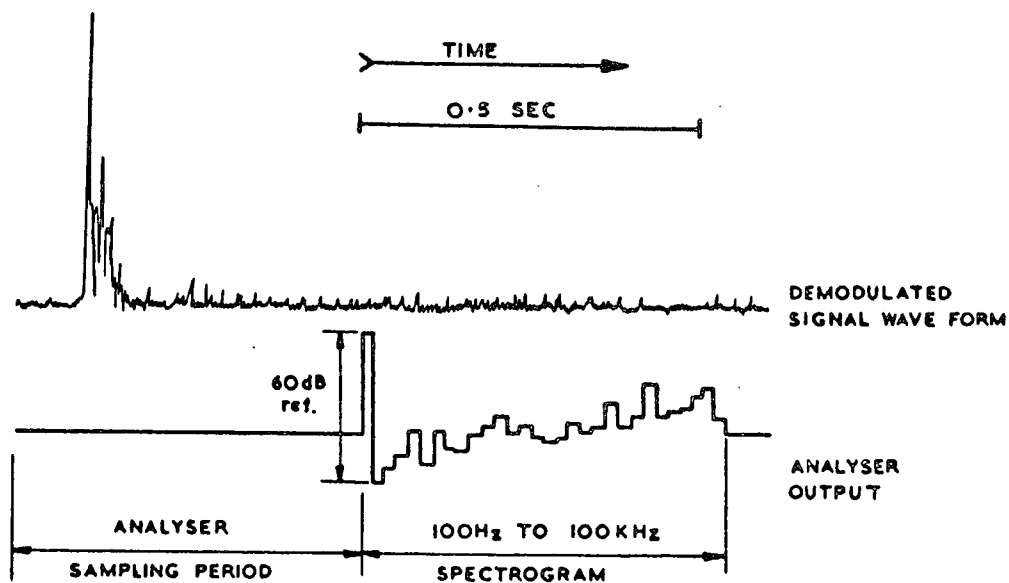
Parallel Filter Real Time Analyser

It has been observed that when each filter in a parallel filter analyser is equipped with its own averaging circuit the rate of output of data is determined by the scanning system. In some models of real time analyser the fast output is achieved by using modern solid state scanning systems to scan the filters sufficiently rapidly to give a continuous display of the spectrum on an oscilloscope so giving the ability to analyse continuously a signal on line.

Another approach to the parallel filter real time analyser does not have rectifiers and averaging circuits on each filter but uses a multichannel detector which samples the filter outputs at about 1 KHz, converts to digital form and computes the root mean square (RMS) which can then be output digitally or reconverted to analogue form for oscilloscope display. The advantage of this technique is a better dynamic range, a very flexible choice of averaging time, e.g., .125 sec to 32 secs and since the averaging is digitally a true representation of equation (1). The output is true RMS regardless of the input waveform; signals with large crest factors can therefore be analysed without error.

A useful feature of real time analysers is the ability to sample and hold transient signals using the appropriate averagin time. Alternatively the signal may be sampled and the spectrum recorded as it is produced. Figures 4A and B illustrate the use of this technique. The experiment carried out in UKAEA was to determine the sound spectrum produced by boiling in sodium. A feature of the noise from this boiling is that it is irregular and impulsive rather than continuous. There is therefore an analysis problem

A. DURING BOILING

TIME

0·5 SEC

DEMODULATED
SIGNAL WAVE FORM

60dB
ref.

ANALYSER
OUTPUT

ANALYSER

100Hz TO 100KHz

SAMPLING PERIOD

SPECTROGRAM

B. BACKGROUND
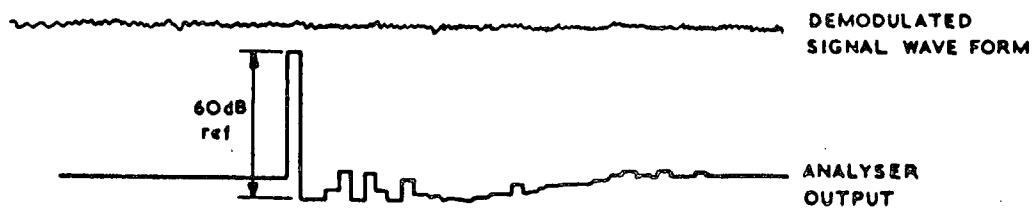
DEMODULATED
SIGNAL WAVE FORM

60dB
ref

ANALYSER
OUTPUT

FIG. 4. DETECTION OF BOILING TRANSIENT WITH REAL TIME
ANALYSER WITH UV RECORDER OUTPUT

to capture the short and realtively infrequent bursts of sound without including a long period of background noise in the sample for analysis. The real time analyser accomplishes this admirably. The figures show sections of an ultra violet recorder output produced on line at the time of the experiment. The second bottom trace represents the signal from the detector while the bottom trace is the output of the analyser showing histogram output. The analyser used here was a digital averaging type with averaging type with averaging time set to $\frac{1}{2}$ sec. ie the sample time is the $\frac{1}{2}$ sec. preceding the output. In the histogram the first two sections give the 0 dB and 60 dB calibration values while the next 30 represent $\frac{1}{3}$ octave filter output covering the range 100 Hz to 80 KHz. Figure B shows the background spectrum where no boiling noise occurred in the sample period.

Swept Filter Real Time Analyser

The new generation hybrid (analogue and digital) real time analysers operate at an analysis rate of at least two orders of magnitude greater than pure analogue devices. These systems digitise the analogue data in real time, feed it into a delay line memory and recirculate it at very high speed. Speed up factors in the range 125 to 500,000 are achieved and are analogous with tape speed transformation. The frequency expanded data is transformed back into analogue form and analysed with a constant bandwidth crystal filter. The analyser based at UKAEA, Springfields produces a 500 point frequency analysis by stepping the filter on by one bandwidth for each pass of the data. (Analysers with finer or coarser resolution are available). Each pass of the data takes 100 usecs thus a full 500 point analysis is available in 50 msecs after filling the memory.

In the normal mode of operation the memory updates itself continuously and so a non-stationary process may be analysed, alternatively, this sequence may be over-ridden either manually or automatically and a short sample of information, e.g., a transient held for detailed analysis.

The analysis system comprises the following modules.

a. real time analyser
b. digital averager
c. X-Y recorder   )
d. paper tape output   )   output devices
e. oscilloscope display)

Computer interfaced analysers are now available. Stationary periodic or transient signals may be analysed using the analyser module only and a suitable output device but random data requires numerous samples to be averaged to provide the required degree of statistical accuracy. This is the digital equivalent of RC averaging and is done by the digital averager.

The analysis system may output into an oscilloscope, to an X-Y plotter with a choice of logarithmic or linear scales, onto paper tape or direct to a computer.

The system has the advantages observed in the parallel filter real time analyser of enabling

a. direct operation on line without requiring tape storage, giving the ability to direct and modify experiments whilst in progress;

b. automatic transient capture facilities. In addition the hybrid system has a more rapid response and finer frequency resolution than parallel filter devices operating in real time.

Typical examples of data analysed by this system are shown in Figures 5, 6 and 7.

Figure 5 shows the spectrum obtained from a strain gauge attached to a nuclear fuel pin excited by hydraulic forces (analysis time = 32 secs). For this experiment the spectra were also digitised and processed on the central computer.

Figure 6 illustrates the transient capture capability of the equipment. Two spectra have been obtained from two transducers attached to an aircraft structure. In the first case the vibration caused by normal turbulence has been measured and then the response to an impulse has been superimposed. This type of analysis shows the principal modes of the structure and whether cross coupling between different modes is likely.

Figure 7 illustrates the full power and speed of this type of system when coupled with a computer. The figure shows the time history of the amplitude spectra for the spoken word "YOUR". The interval between succession spectra is 24 msecs. A computer with a large store and fast access rate is the ideal matching device for storing this type of analysis. This example contains 7680 data points achieved in 0.768 secs. Other fast output devices used with success are high speed cine cameras synchronised with the filter sweep and X-Y-Z recorders. The figure also suggests other applications in the medical field for example electrocardiography and electroencephalography.

Twin channel systems are available with computer backing to derive correlation and transfer functions.

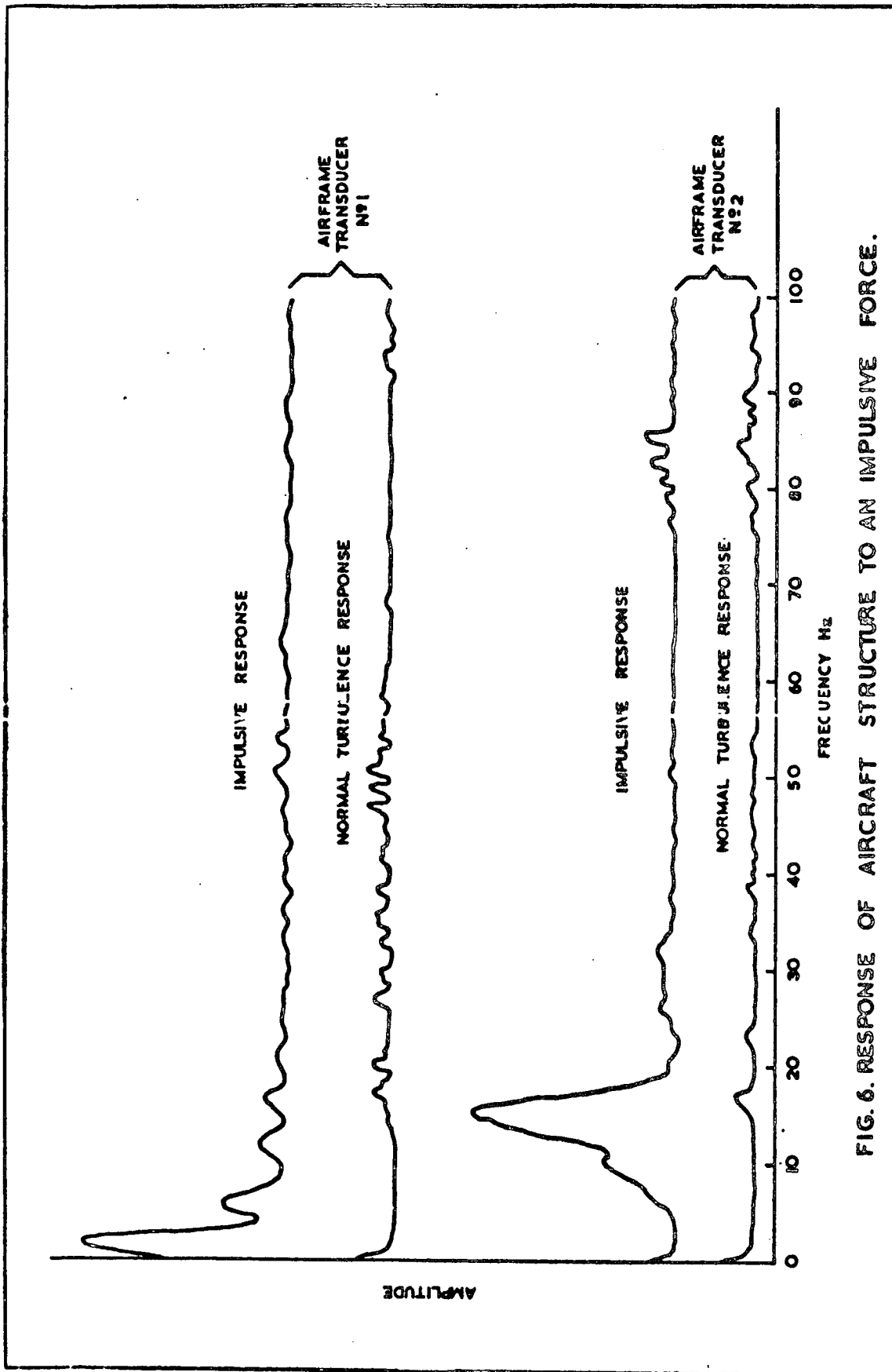FIG. 5. STRAIN SPECTRUM ON NUCLEAR FUEL PIN
EXCITED BY HYDRAULIC FORCES.
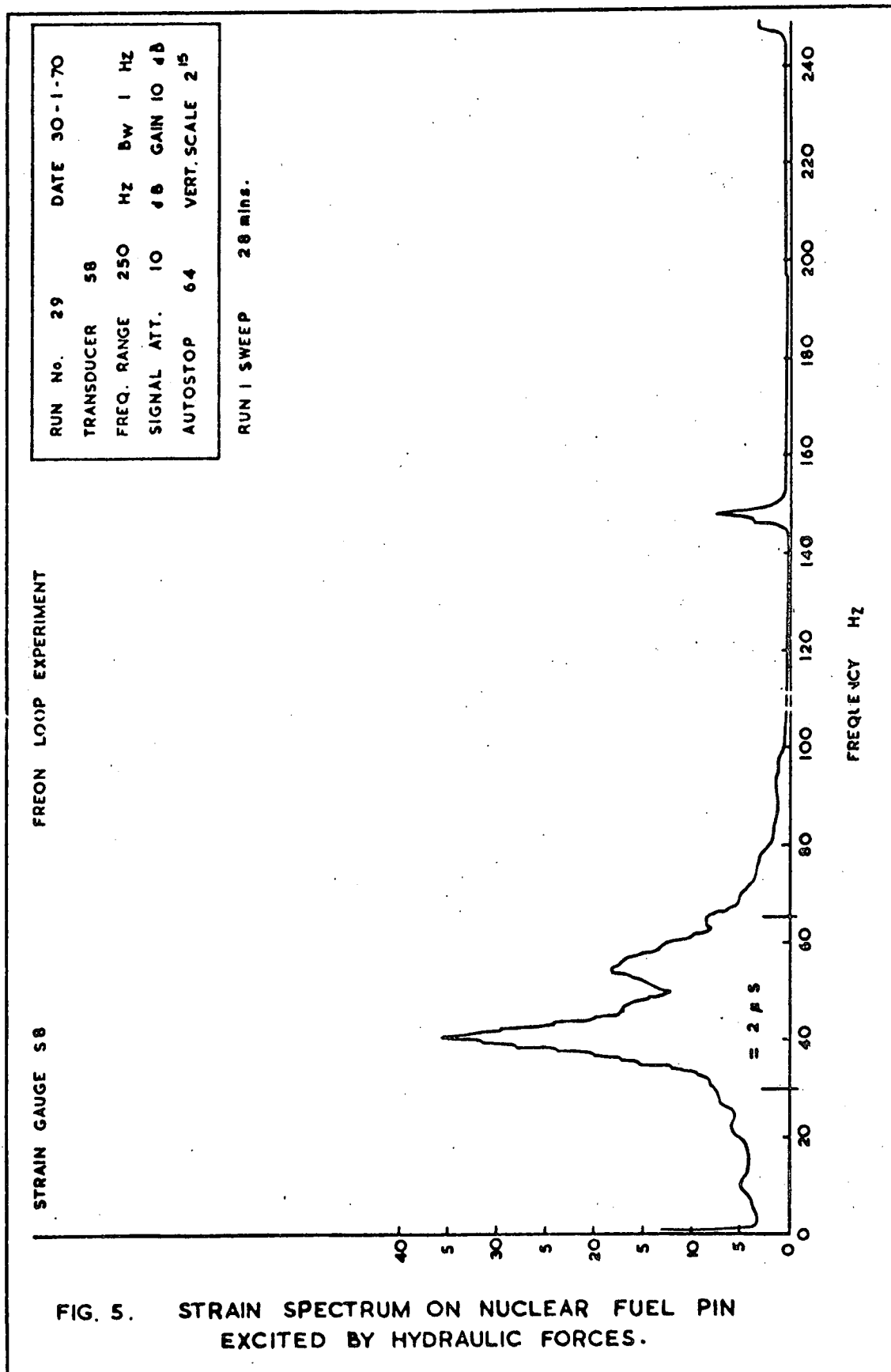
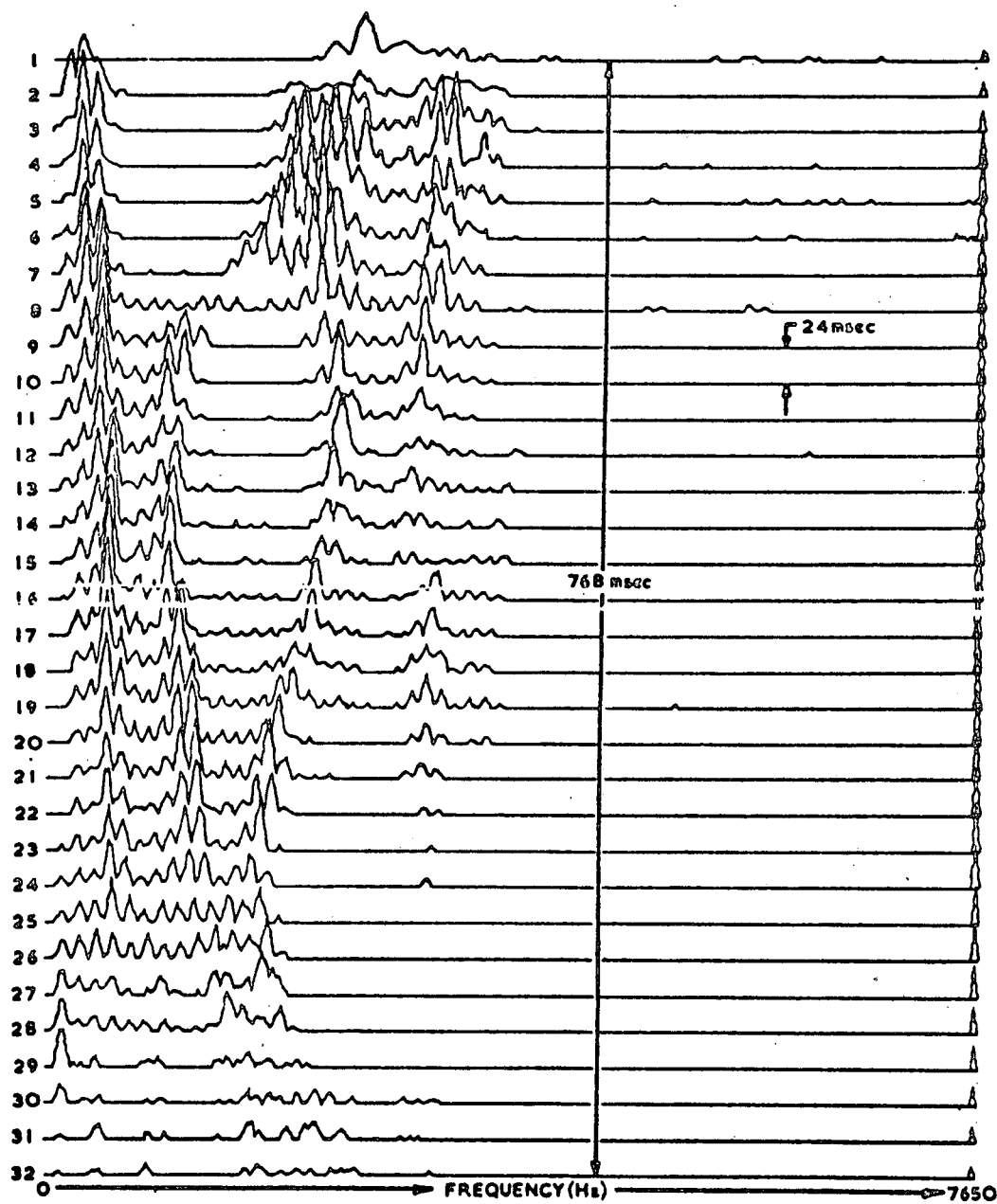FIG. 6. RESPONSE OF AIRCRAFT STRUCTURE TO AN IMPULSIVE FORCE.

Dg-14

FIG. 7. COMPUTER-PLOTTED SEQUENCE OF AMPLITUDE SPECTRA
FOR THE SPOKEN WORD 'YOUR'

ADDENDUM H

STRUCTURE BORNE ACOUSTICS PROCESSOR

INTRODUCTION

This addendum is directed toward definition of a processor or logic device for the processing of basic performance data originating at mechanical line replaceable units (LRU) such as a pump, pneumatic regulator, valve, et al. Sensor data resulting from state-of-the art instrumentation techniques are examined to evaluate logic device physical and functional configuration. Functional integration of this concept is consistent with advanced checkout philosophies. Three logic device implementation concepts are discussed, each having application depending upon mechanical component density, complexity, and/or similarity. Guidelines for application of each concept are discussed.

LOGIC DEVICE APPLICATION

The deployment of a logic device which will satisfy the overall functions of readiness assessment, monitoring, and controlling of critical components is dependent primarily on the overall system philosophy, component density, and similarities. Although there are many similarities between the three implementation concepts depicted in Figure 1, the logic device discussed herein is in reference to Concept 1 which utilizes a dedicated logic device for each critical component. The logic device described assumes that the included functions will be performed in close proximity to the mechanical component.

System concepts may dictate that much of the processing function should be accomplished in a centralized processor as depicted in Concepts 2 and 3. Table 1 highlights the conceptual differences. Sizing of a processor based on concept 3 is discussed in Reference Addendum A, Section I, #39.

CONCEPT #1 - LOGIC DEVICE FOR EACH COMPONENT
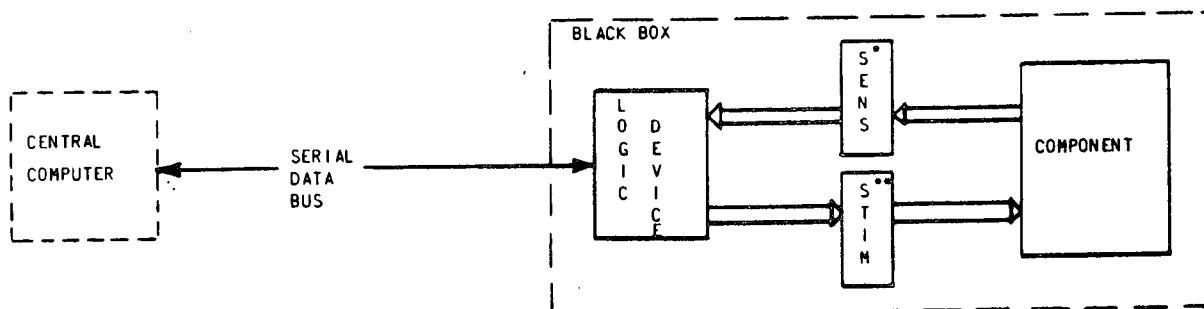
CONCEPT #2 - LOGIC DEVICE FOR EACH COMPONENT
         - LOGIC DEVICE FOR GROUPS OF COMPONENTS
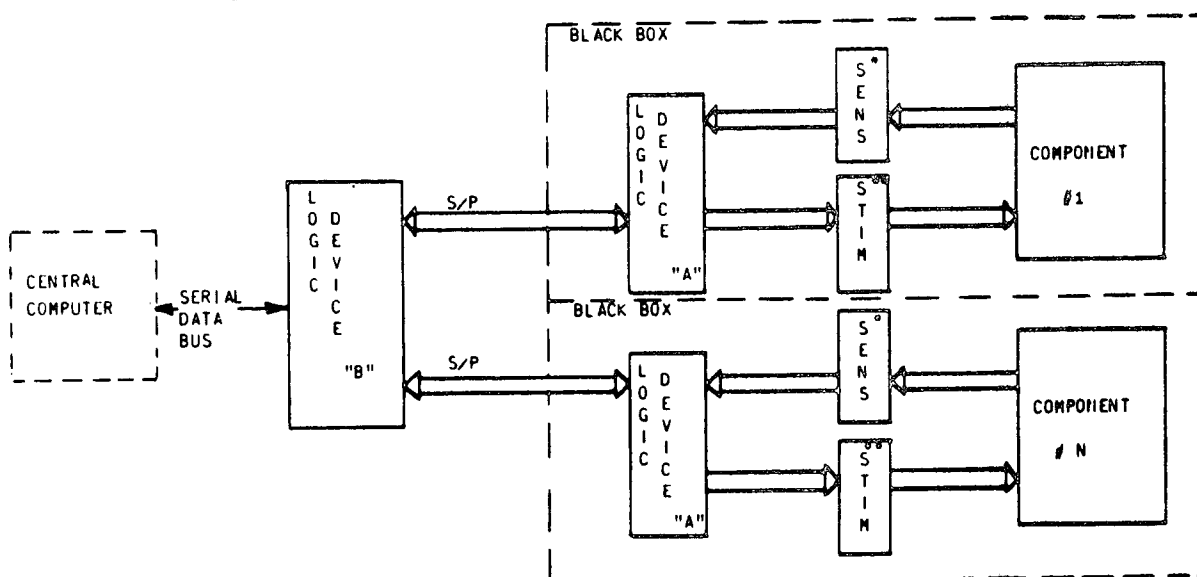
CONCEPT #3 - LOGIC DEVICE FOR GROUPS OF COMPONENTS

*   SENSORS
**   STIMULUS
S/P   SERIAL/
       PARALLEL

CONFIGURATION CONCEPTS

Figure 1. Implementation Concepts

Table 1

Concept Matrix

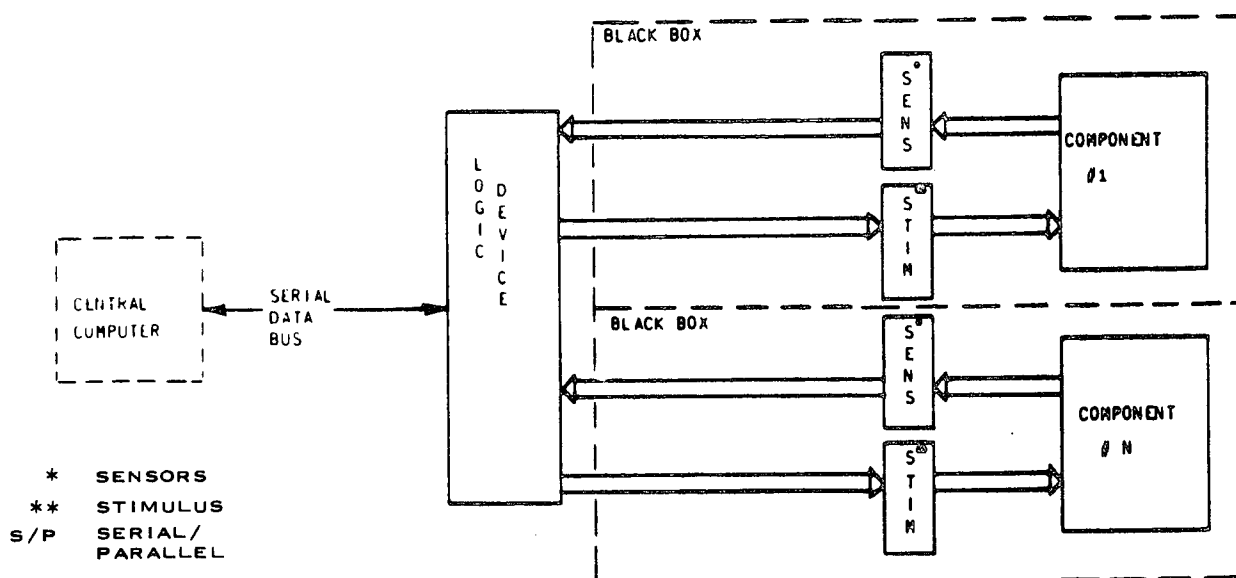| CONCEPTS / CRITERIA	CONCEPT #1	CONCEPT #2	CONCEPT #3
Readiness Determined at Component	Readiness would be determined at the component.	Readiness would be determined by logic device "B" serving several components.	Readiness would be determined by logic device serving several components.
Standardization and Modular Techniques	Compatible with modular techniques. Logic device will be unique for each type component.	Compatible with modular techniques. Logic device "A" will be unique for each type component. Logic device "3" could be generally standardized.	Compatible with modular techniques. Logic device could generally be standardized pending application and signal conditioning requirements.
Size & Weight Per Component Monitored	Largest	Reduced by degree in which time sharing is utilized.	Reduced by degree of which time sharing is utilized.
Cost	Highest Cost — each logic device requires total functions for component assessment.	Reduced to the degree in which the components time share logic device "B".	Reduced to the degree in which logic device and signal cond. is time shared.
Sensor Types	Capable of handling state-of-the-art sensors. Logic device is dedicated to component.	Capable of handling state-of-the-art sensors. Limited by number of routines required to assess components.	Capable of handling state-of-the-art sensors. Limited by number of sensor types and logic routines required to assess components.
Diagnostic Routines Required	No time sharing of identical diagnostic routines between components.	Diagnostic routines could be time shared with many components.	Diagnostic routines could be time shared with many components.
Data Bus Concept Utilization	Would utilize concept and would best be suited to widely separated components.	Would utilize data bus concept. Interface between logic device "A" and "B" is serial/parallel.	Would utilize data bus concept between logic device and central computer only - remaining interfaces are parallel.
Component Density	Would be ideal for very low density, very complex components.	Well suited for high density components using unique sensing techniques.	Well suited for high density components with identical sensing techniques. Signal conditioning could be time shared at the logic device.

The typical application of the logic device may require varying degrees of dedication, measurement acquisition, and processing capability. For this reason, the logic device design should be modularized, to the extent possible, such that the logic device configuration can be selected based on the LRU requirements for readiness assessment.

LOGIC DEVICE FUNCTIONS

Mechanical device readiness assessment parameters can be selected, and instrumentation is available, or can be developed, to provide electronic presentation of those parameters; however, processing and interpretation of this data, to translate it into meaningful go, no-go caution signals, must employ digital logic.

The logic device provides those functions necessary to automatically determine the operational status of the mechanical component. These functions are:

- Measurement Acquisition.
- Data Processing.
- Status Processing.
- Memory and Software.
- Self-Test.
- Bidirectional Communications.
- Stimuli Generation and Distribution.

Figure 2 depicts the logic device and its functional interfaces.

LOGIC DEVICE CAPABILITY

Status Processing

Status processing functions within the logic device will provide the component status continuously or when requested by an external source. The component status will be one of go, no-go, and caution. The status of the component will be formatted into a digital word compatible with data bus techniques. The go status indicates that the component is well and that no degradation has been sensed either by direct measurement or by the diagnostic routines within the logic device.

Dh-4
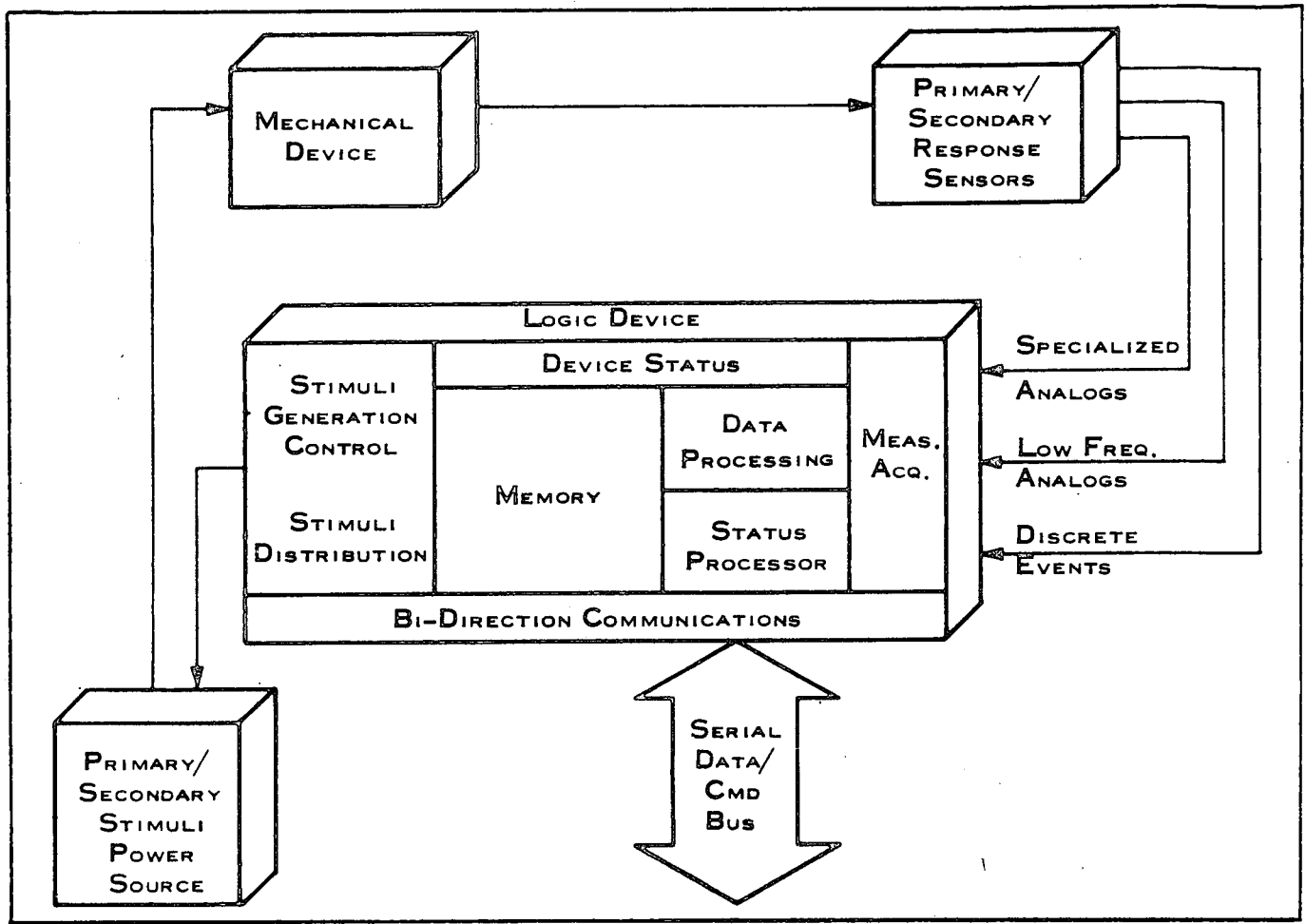
Figure 2. Logic Device Functional Interfaces

The caution status indicates that component performance degradation has been sensed either by direct measurement or by diagnostic routines. The caution status further indicates that the component is still capable of performing its intended function within its operational limits. The caution status will be accompanied by an explanation identifying the component approaching possible malfunction and the cause, determined by the logic device, thus providing fault prediction at the component or line replaceable unit level.

The no-go status indicates that the component is not capable of operating within normal operational limits. The no-go status will be accompanied by an identification of the malfunctioned component and the cause, determined by the logic device, thus providing fault isolation at the component or LRU level.

Memory and Software

Memory and software contained within the logic device must be adequate to accomplish the processing functions. This includes memory for program storage as well as data storage for stimulus distribution and generation, measurement acquisition, data processing, status processing, bidirectional communication, and logic device self-test.

Because of the number of sensor techniques and the processing techniques required to assess the readiness of a given component, the software development will require an extensive verification program to thoroughly evaluate the logic device-mechanical component relationship. This evaluation will be necessary to confirm the test point location, sensor selection (sensitivity and selectivity), diagnostic routines, signal conditioning, stimulus generation, and the overall ability of the logic device to assess the readiness, predict failures, and isolate the fault. Complete specifications of test algorithms will require that special attention be given to each logic device input when component assessment is completely automated.

Problems can be anticipated in the generation of algorithm specification. It is generally difficult to specify necessary and sufficient test conditions or limits for all possible states that may exist. Further, there are no clear-cut rules or guidelines as to what constitutes a reasonable limit specification, as an example, complex wave-form analysis. This means that the logic device must have the necessary flexibility to meet unspecified requirements with a minimum effort. Experience with logic devices indicates that programmable memory may be replaced with Read Only Memory (ROM) at that point in time that the full test and diagnostic procedures for a particular device have been tested, tried, and found to be true.

Finding the most effective discriminant or discriminants for each mechanical component, in the operational environment, is a problem having two basic solutions. Statistically, if a sufficiently large sample of signatures from good and malfunctioning components is available, it is possible to evaluate a number of discriminants and to select the most effective. The success of this approach depends entirely upon a good statistical sample. In many cases, such a sample is not available or would be unreasonably expensive to obtain. A second approach is based on the understanding of the mechanical component and the process by which a particular signature is generated. This usually requires a thorough study of the mechanics of the component, operational characteristics, and environment, so that a model for normal and abnormal signatures can

Dh-6

be established. Once this is done, test algorithms and limits can be selected with a good probability of success and can be then optimized experimentally.

Logic Device Status (Self-Test)

Each logic device will be capable of determining internal status and operational readiness by self-test.

Bidirectional Communications

The two-way communications function will be performed in a manner compatible with the existing data bus concept. The data bus concept is defined as a single cable which provides serial data transfer, in either direction, between any of the data bus parallel interfaces. The bidirectional communication function includes receiver, decoder, verification, transmission, control, and buffer subfunctions. The data bus could be redundant with appropriate encoding/decoding modifications to the bidirectional communication function.

Stimuli Generation and Distribution

Primary stimuli are the result of commands generated at an external source, received, decoded and verified via the bidirectional communication and then transferred to the distributor in a form ready for execution. Secondary stimuli are commands generated internal to the logic device and are necessary for stimulating the mechanical component for determining readiness. Both primary and secondary stimuli can be discrete or analog.

Measurement Acquisition and Data Processing

Accomplishing component readiness assessment is entirely dependent on determining the component status indicators, selecting the proper sensors, and then selecting the processing necessary to isolate the discriminant. A logic device discriminant is defined as processed information, derived from data collected at the component, that can be correlated to the performance and operational condition of the component.

Figure 3 represents discriminants based on three sensor categories, specialized analogs, analogs, and discretes. The selection of the discriminants and transducers which will provide component readiness assessment varies from component to component. The General Electric Company study indicated that a typical component would require six monitoring points: 1 specialized analog, 2 analogs, and 3 discretes.
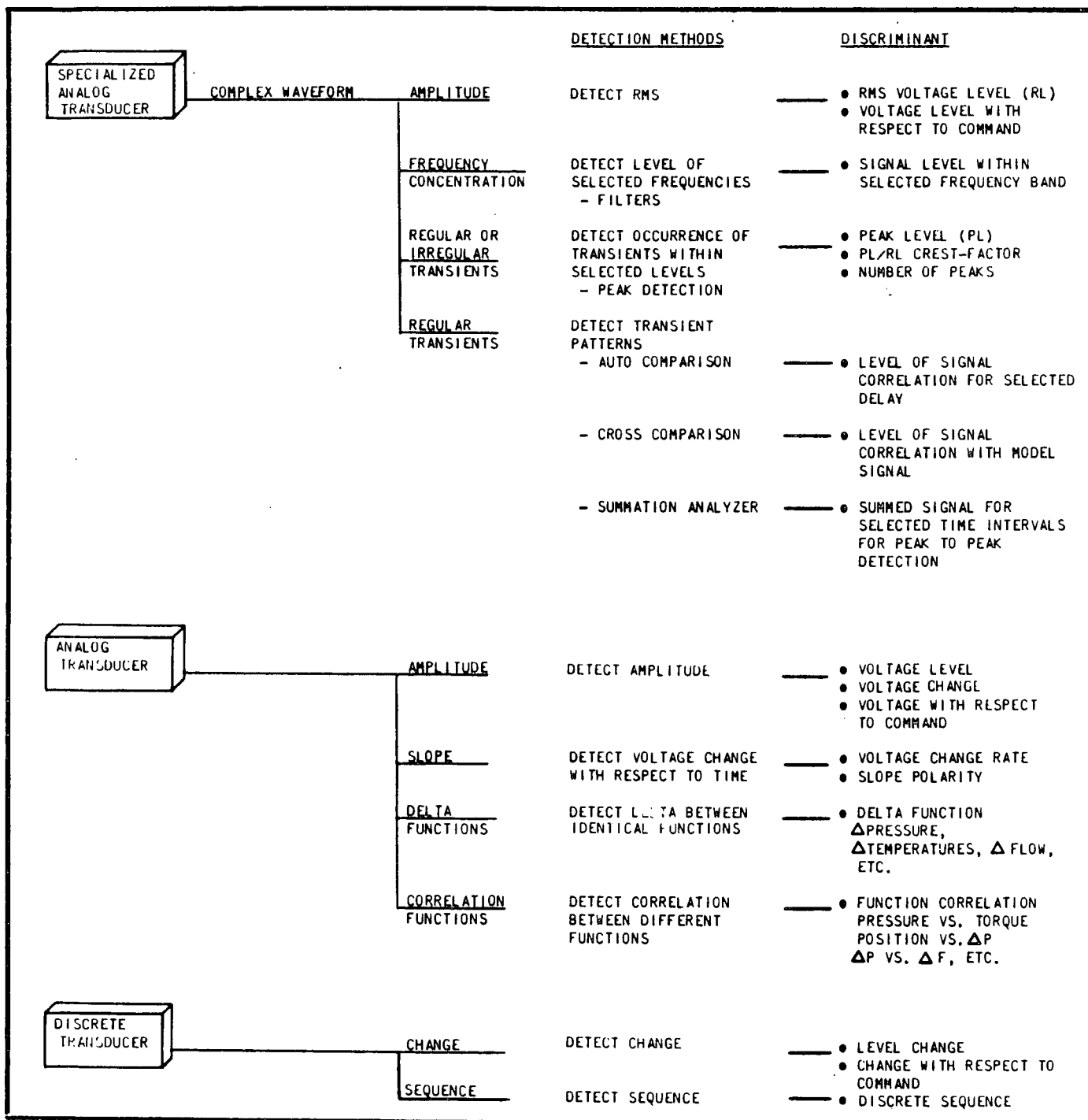
Figure 3. Identification of Discriminants

In many instances the same computation or preprocessing function could be performed with either analog or digital techniques. In these instances the logic device would utilize the technique or combination of techniques that best satisfy the design objective.

a. Specialized Analogs—Specialized analogs are considered to be complex waveforms such as an accelerometer output used in structure borne acoustics with a frequency content of 0 to 50 kHz. Capability of the logic device includes the detection of:

- RMS signal levels.
- Signal levels within selected frequency bands.
- Irregular transients.
- Transient patterns.

b. Analogs—Analogs in this category are considered to be of low frequency (0 to 1 kHz); such as those resulting from temperature, pressure, and flow sensors. Frequently, information pertaining to the mechanical component status, particularly fault prediction, can be determined by isolating those discriminants contained in low frequency analogs. Capability of the logic device includes the detection of:

- Amplitude.
- Slope.
- Delta between identical functions.
- Correlation between different functions.

c. Discretes—Discretes in this category are considered to be event type such as those used for sensing discrete liquid level, valve closures, and other discrete sensors used primarily for component monitoring as opposed to readiness assessment. Capability of the logic device includes the detection of:

- Discrete changes.
- Discrete sequences.

LOGIC DEVICE PHYSICAL CHARACTERISTICS AND COST

The logic device is critical to the success of automatically determining component readiness. The logic device characteristics (size, weight, and power consumption) are critical in determining the application or deployment of the device in a total system. Because of this criticality, a "preliminary" assessment was made relative to its characteristics and material cost based on existing technology and off-the-shelf piece parts.

Characteristics and cost of the logic device are based on the logic device functional requirements previously discussed and the assumptions and supporting rationale utilized to establish the characteristics which follow:

a. <u>Logic Device Processing Capability</u>—The capability of the device was defined to satisfy the processing requirements for one relatively complex component, requiring those diagnostic routines necessary to identify the discriminants as depicted in Figure 3.

b. <u>Dedication of Logic Device</u>—For the purpose of this exercise, the logic device was considered to be dedicated to the component (i.e., Concept 1). The logic device would be capable of processing:

- 6 Transducer Inputs:
    - 1 Specialized analog.
    - 2 Low frequency analogs.
    - 3 Discretes.

- 4 Output Commands:
    - 2 Analog stimuli.
    - 2 Discrete stimuli.

- 1 Serial Bidirectional Digital Data Bus Interface with:
    - Multiple inputs (commands).
    - Multiple outputs (status, performance data).

c. <u>Building Block Construction</u>—The logic device would be developed from a family of functional modules which will take maximum advantage of the rapidly improving large-scale integration semiconductor technology.

d. <u>Modular Organization</u>—The logic device would be organized in a modular arrangement employing a minimum number of unique building block modules. The functional modularity will provide overall logic device flexibility by permitting incremental configurations that would satisfy specific operational and component readiness assessment requirements.

e. <u>Memory Selection</u>—Based on the functional requirements, a combination of Read-Only-Memory (ROM) and Random-Access-Memory (RAM) was selected. The selection criteria utilized was power consumption, size, cost, and speed although speed was not a major consideration. The selection resulted in 2048 8-bit words of static metal-oxide semiconductor RAM and 2048 8-bit words of ROM.

f. <u>Stimuli Distribution</u>—Stimuli, both analog and discrete, would be limited to 100 milliamperes from the logic device. For those stimuli requiring additional power, the logic device will provide a pilot control to a stimuli power source external to the logic device.

g. Storage—No off-line storage will be required by the logic device. Long-term trend analysis will be accomplished by a higher level computational device.

h. Piece Part Selection—Only off-the-shelf piece parts were selected, and quantity purchase prices were used.

i. Power—Regulated ±15 volts and +5 volts will be provided to the logic device.

j. Analog Conversion—Analogs were converted to 8-bit binary coded decimal form. The 8-bit resolution or an output accuracy of ±0.4 percent was felt to be adequate for a majority of the applications.

Table 2 depicts the summary results of this exercise broken down by functional elements of the logic device.

Table 2
Logic Device Characteristics and Cost

Function	Size (Cubic Inches)	Weight (Pounds)	Power (Watts)	Material Cost Estimates (Dollars)
Bidirectional Communication	16	0.5	1	500.00
Stimuli Generation and Dist.	8	0.3	1	200.00
Processing	64	4.0	4	2,000.00
Measurement Acquisition	34	2.4	7.4	1,150.00
Memory	20	1.0	13	1,700.00
Self-Test	8	0.3	1	250.00
Packaging	64	1.0	—	500.00
Total	214	9.5	27.4	6,300.00

It should be emphasized that logic chips at the component level having only fractional "Logic Device" capability as defined in this discussion could be implemented at a considerable reduction in price.

ADDENDUM I

SBA SYSTEM HARDWARE

CHECKLIST

This addendum was excerpted from the Endevco Piezoelectric Accelerometer
Instrumentation Manual with permission from the Dynamic Instrument Division
of Endevco.

CHECK LIST – INSTRUMENT SELECTION

Transducer

Will the accelerometer operate satisfactorily in the measurement environment?

Check:
- Temperature Range
- Maximum Shock and Vibration
- Humidity
- Pressure
- Acoustic Level
- Corrosive Gases

- Magnetic and RF Fields
- Nuclear Radiation
- Salt Spray
- Transient Temperatures
- Bending of Mounting Surface

Will the accelerometer characteristics provide the desired data accuracy?

Check:
- Sensitivity
- Frequency Response
  - Resonant Frequency
  - Internal Capacity
- Transverse Sensitivity
- Amplitude Linearity

- Temperature Deviation
- Weight
- Internal Resistance at
  - Maximum Temperature
- Calibration Accuracy
- Strain Sensitivity

Is the unit in good condition and ready to use?

Check:
- Up-to-Date Calibration
- Physical Condition
  - Case
  - Mounting Surface
  - Connector
  - Mounting Threads

- Inspect for Clean Connector
- Internal Resistance

Is the proper stud being used for this application?

Check:
- Insulating Stud Required?
  - Ground Loops
  - Calibration Simulation
- Cementing Stud Required?
- Thread Size

Is the stud in good condition and ready to use?

Check:
- Mounting Surface Condition
- Thread Condition
- Burred End Slots

- Insulated Stud
  - Insulation Resistance O. K.
  - Stud Damage by Over Torquing

Di-2

Cable

Will the cable operate satisfactorily in the measurement of environment?

    Check: Temperature Range

Will the cable characteristics provide the desired data accuracy?

    Check: Low Noise
                    Size and Weight
                    Flexibility
                    Sealed Connection Required?

Is the cable in good condition and ready for use?

    Check: Physical Condition
                          Cable Kinked, Crushed?
                          Connector Threads, Center Pin O. K. ?
                    Inspect for Clean Connectors
                    Continuity
                    Insulation Resistance
                    Capacitance

Amplifier

Will the amplifier operate satisfactorily in the measurement environment?

    Check: Temperature Range   Corrosive Gases
                    Maximum Shock and Vibration   Magnetic and RF Fields
                    Humidity   Nuclear Radiation
                    Pressure   Salt Spray
                    Acoustic Level

Is this the proper amplifier for the application?

    Check: Long Input Lines?
                        Need for Driven Shield Amplifier
                        Need for Charge Amplifier
                    Long Output Lines?
                        Need for Power Amplifier
                    Airborne?
                        Need for Solid-State Potted Amplifier

Will the amplifier characteristics provide the desired data accuracy?

Check: Gain   Output Current and Voltage
           Frequency Response   Residual Noise
           Linearity   Input Impedance
           Stability   Transient Response
           Phase Shift   Overload Capability

Is the unit in good condition and ready to use?

Check: Up-to-Date Calibration
           Physical Condition
               Connectors
               Case
               Output Cables
           Inspect for Clean Connectors

Readout

Does the remainder of the system, including any additional amplifiers, filters, and readout devices introduce any limitation that will tend to degrade the transducer-amplifier characteristics?

Check: All of previous check items, plus adequate resolution

CHECK LIST - INSTALLATION

Transducer

Stud Mounting   Mounting Surface Clean and Flat
                       Transducer Base Surface Clean and Flat
                       Hole Drilled and Tapped Deep Enough
                       Correct Tap Size?
                       Hole Properly Aligned Perpendicular to Mounting Surface
                       (Stud Threads Lubricated)
                       Accelerometer Mounted with Recommended Torque
                       Use Light Oil for High Frequency Measurements above 5 kHz

Cement Mounting   Mounting Surface Clean and Flat
                           (Dental Cement for Uneven Surfaces)
                       Cement Cured Properly
                       Accelerometer Mounted to Cementing Stud with
                           Recommended Torque

Di-4

Cable

Check: Cable Connected Securely to Accelerometer
Cable Tied Down 2 - 3 " from Connector
Excess Cable Coiled and Tied Down .
Drip Loop Provided
Connectors Sealed and Potted, if Required
Cable Connected Securely to Amplifier

Amplifier

Check: Mounted Securely
All Cable Connections Secure
Gain Hole Cover Sealed, if Required
Recommended Grounding in Use